AN APPROACH TO THE ESTIMATION OF LIFE CYCLE COSTS OF A FIBER-OPTIC APPLICATION IN MILITARY AIRCRAFT

John Michael McGrath

NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

AN APPROACH TO THE ESTIMATION OF
LIFE CYCLE COSTS OF A FIBER-OPTIC
APPLICATION IN MILITARY AIRCRAFT

by

John Michael McGrath
Kenneth Ralph Michna

September 1975

Thesis Advisor: Carl R. Jones

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) An Approach to the Estimation of Life Cycle Costs of a Fiber-Optic Application in Military Aircraft		5. TYPE OF REPORT & PERIOD COVERED Master's Thesis; September 1975 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) John Michael McGrath Kenneth Ralph Michna		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Postgraduate School Monterey, California 93940		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Postgraduate School Monterey, California 93940		12. REPORT DATE September 1975 13. NUMBER OF PAGES 165
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) Naval Postgraduate School Monterey, California 93940		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Optical fibers, fiber optics, optical waveguides, light emitting diodes, PIN diodes, economic analysis, cost effectiveness analysis, life cycle cost model

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

As significant technological advances in fiber optics and optical data transmission methods are being made, it is necessary to develop appropriate methods for estimating life cycle costs for alternative coaxial/twisted pair wire and optical fiber avionics. Measures of effectiveness are suggested for each alternative system. An approach, which structures the technological and demand uncertainties of

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE
(Page 1) S/N 0102-014-6601

20. Abstract (cont'd)
fiber optics, is developed through scenarios as a means of relating cost and effectiveness. It is suggested that Delphi and experience curve techniques be used in conjunction with ordered scenarios as a technological forecasting technique for estimation of life cycle costs of fiber optics. In addition, a review of the historical and technological background of fiber optics and their application to the Naval Electronics Laboratory Center (NELC) A-7 Airborne Light Optical Fiber Technology (ALOFT) Program is included.

An Approach to the Estimation of Life Cycle Costs of a Fiber-Optic Application in Military Aircraft

by

John Michael McGrath
Lieutenant Commander, United States Navy
B.S., United States Naval Academy, 1962

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN MANAGEMENT

and

Kenneth Ralph Michna
Lieutenant Commander, United States Navy
A.B., Wabash College, 1965

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN OPERATIONS RESEARCH

from the
NAVAL POSTGRADUATE SCHOOL
September 1975

ABSTRACT

As significant technological advances in fiber optics and optical data transmission methods are being made, it is necessary to develop appropriate methods for estimating life cycle costs for alternative coaxial/twisted pair wire and optical fiber avionics. Measures of effectiveness are suggested for each alternative system. An approach, which structures the technological and demand uncertainties of fiber optics, is developed through scenarios as a means of relating cost and effectiveness. It is suggested that Delphi and experience curve techniques be used in conjunction with ordered scenarios as a technological forecasting technique for estimation of life cycle costs of fiber optics. In addition, a review of the historical and technological background of fiber optics and their application to the Naval Electronics Laboratory Center (NELC) A-7 Airborne Light Optical Fiber Technology (ALOFT) Program is included.

TABLE OF CONTENTS

LIST OF FIGURES

Figure		Page

ACKNOWLEDGEMENT

The authors wish to express their appreciation to Associate Professor Carl R. Jones for his encouragement and assistance in this work.

The authors also wish to express their appreciation to LCDR J. R. Ellis, Mr. Roger Greenwell, and other personnel of NELC who unselfishly shared their time and materials to assist in this work.

I. INTRODUCTION

Present day avionics in military aircraft utilize twisted shielded pair wire and/or coaxial cable to transfer signal data. These data link subsystems reflect post-World War II state of the art in electronic development. Electronic signal transmission by this means exposes avionics to potential operational degradation and damage because of the susceptibility of metallic conductors to electromagnetic interference, radio-frequency interference, and nuclear-generated electromagnetic pulse. Other sources of electronic interference such as cross-talk, ground looping, reflection, and short-circuit loading also degrade system operation.

A recent technological breakthrough in the field of fiber optics has made fiber-optic data link applications technically feasible, and perhaps desirable, for use in military aircraft avionics systems. Fiber optics technology does offer several significant advantages for avionics data link subsystems. The primary advantages are that it: (1) is not susceptible to electromagnetic interference (EMI) nor to electromagnetic pulse (EMP) associated with a nuclear blast; (2) does not generate EMI; (3) is isolated from ground plane signals; and (4) is capable of higher data rate transmission.

As a result of feasibility tests and demonstrations conducted or sponsored by Naval Electronics Laboratory Center (NELC), San Diego, approval was gained from the Assistant Secretary of the Navy for Research and Development to implement a two-year feasibility program to install fiber optics components (fiber-optic cables, light sources, light detectors, and connectors) in place of standard twisted pair wire and coaxial cable for selected components of the Navigation/ Weapons Delivery System (N/WDS) of an operational A-7E Corsair II light jet attack aircraft. The program, called the A-7 Airborne Light Optical Fiber Technology (ALOFT) Demonstration, is a feasibility demonstration to determine the information transfer capability of an aircraft avionics system through point-to-point applications of fiber optics.

Concurrent with the A-7 ALOFT Demonstration checkout, test and evaluation, an economic analysis was desired by NELC for the two alternative systems; coaxial cabling and fiber-optic cabling. These two alternatives, together with their associated components, will hereafter be referred to as "coax" and "fiber optics."

The basic format of an economic analysis involves the determination of the cost and effectiveness of competing alternatives. A life cycle cost model, as defined by NELC and Naval Postgraduate School (NPS) students is used as the costing basis for the two alternatives.

A contractor will perform the costing of the coax alternative. He will also determine the measures of effectiveness for both the coax and fiber optics systems. Naval Postgraduate School students will perform the costing effort of the fiber optics alternative. The authors of this thesis perform a preliminary costing effort for the fiber optics alternative by developing an approach to costing fiber optics as an emerging technology. NPS students and NELC systems analysts personnel will coordinate future efforts toward the desired objective of numerical estimation of fiber optics life cycle costs.

As a baseline thesis for follow-on NPS theses students, the authors have discussed the historical and technological background of fiber optics as well as the background of the A-7 ALOFT Demonstration. A general discussion of a cost-effectiveness analysis is presented together with possible measures of effectiveness (MOEs) for data transfer.

Since fiber optics cost data is either non-existent or available only on a prototype basis, the authors' basic approach to costing fiber optics is done through scenarios. Scenarios offer a means of ordering the uncertainties of an emerging technology. They define the possible futures of the fiber optics industry and its related technology. Three sample scenarios developed by the authors provide specific time-related estimates as to civilian/military demand, growth rates,

standardization and technological development. These representative scenarios are meant to provide the basis from which cost estimates could be made.

Two exploratory techniques, Delphi and experience curves, are discussed as they pertain to the costing of an emerging fiber-optic technology. A sample Delphi questionnaire is developed as a means of soliciting forecasts from a panel of experts in order to deal with specific uncertainties associated with fiber optics. (e.g. When will production bases be established for fiber optics components?) The information gained from the Delphi survey can be used to refine the estimates contained in the scenarios as well as minimize the number of possible scenarios.

Experience curve evidence is discussed as a means for forecasting unit cost reduction as the fiber optics experience base accumulates. The information required for using experience curves is provided by the scenarios. Experience curves can then be used as a means of predicting the cost behavior of components relating to fiber-optic technology.

It is felt by the authors that these techniques; scenario-writing, Delphi and experience curves, can be combined as a cost-predictive method to estimate component prices of an emerging technology such as fiber optics. These techniques can then provide a means of estimating costs for the life cycle

cost model elements used in a cost-effectiveness study. Not only will the fiber-optic component procurement costs be estimated, but the costs to operate and maintain a fiber-optic system will also be determined through future efforts.

This thesis, then, is the first step in developing a cost-effectiveness study which could aid in making decisions concerning the use of coax or fiber optics in the next series of military aircraft to be designed and built (VAX, VFX, VPX, etc.).

It is the basic conclusion of the authors that the emerging fiber-optic technology deserves full and continuing effort and attention by research and development (R&D) agencies. Even if the results of initial cost-effectiveness studies are such that the decision is made to <u>not</u> use fiber optics in the next generation of aircraft, the authors feel that it would be a mistake to cut back or reduce fiber optics R&D funding. The military services are pursuing extremely meaningful and productive research and development in a field containing great potential for future benefits to the military services in general. It is expected that fiber optics will be used in some future generation of military aircraft and weapons systems. These future weapons systems would be the beneficiaries of today's efforts from the development of this emerging technology.

II. BACKGROUND

A. HISTORICAL BACKGROUND

1. Background of Glass Fibers/Fiber Optics

Glass has been used in a multitude of applications from very early times. The earliest glass objects come from Egypt and are dated from circa 2500 B.C. The first vessels of glass were manufactured in Egypt under the 18th dynasty, particularly from the reign of Amenhotep II (1448-20 B.C.) onward. The possibility of drawing hot glass into threads was recognized in the Rhineland during the late Roman empire as well as in ancient Egypt and such threads were wound around vessels as a decoration.

In the 18th century, fine threads were prepared from a heat softened glass rod by using a "spinning wheel" process. The next development was a mechanized drawing process by attaching the fiber from the heat-softened rod to the surface of a large revolving drum. In 1908, G. von Pazsiczky replaced the rods with a refractory glass-melting chamber that had a series of holes in the bottom to provide drawing points. A different method of production was developed in 1929 whereby the application of centrifical force forced the glass through radial serrations resulting in a tangled mass of fibers. [16]

It is entirely possible that early Egyptian and Grecian Glassblowers observed the phenomenon of multiple total internal reflections in conducting light along transparent glass cylinders, and in fact, there are a number of unsubstantiated historical claims. However, the earliest recorded scientific demonstration of the phenomenon of total internal reflection was recorded by John Tyndall at the Royal Society in England in 1870. In his demonstration, he used an illuminated vessel of water to show that when a stream of water was allowed to flow through a hole in the side of the vessel, light was conducted along the curved path of the stream. D. Hondros and P. Debye followed the work of Tyndall by doing some theoretical studies on optical wave propagation in fibers in 1910, but little else was done in the way of experimentation.

The phenomenon described by Tyndall was disregarded and lay dormant until 1927, when J.L. Baird in England and C.W. Hansell in the United States considered the possibility of using uncoated fibers in the field of television to transmit and scan an image. They were followed closely by H. Lamm of Germany who used a crude assembly of quartz fibers to demonstrate the basic image and light transmission properties of fibers. Activity in this area then all but ceased for two decades. [25]

Quite unrelated to previous experiments with glass fibers as light conductors, manufacturing methods for producing glass fibers were being perfected. For example, in 1938 the Owens-Illinois Glass Company joined with the Corning Glass Works to form a new independent glass fiber firm. The company, the Owens-Corning Fiberglass Corporation, developed large-scale production methods to produce glass fibers. The spun glass method allowed continuous threads to be drawn from bushings provided with 100-400 small orifices. The threads falling from these orifices were gathered together and passed over a sizing pad onto a spool on a high-speed winder. The resulting fiber had a diameter of around 0.00022 in. (the material contained in one glass marble 3/4 in. in diameter would yield about 97 miles of single filament). [15]

A new burst of activity began in the year 1951, when A.C.S. van Heel in Holland and H.H. Hopkins and N.S. Kapany at the Imperial College in London independently initiated studies on the transmission of images along an aligned bundle of flexible glass fibers. Kapany, B.I. Hirschowitz, and others then developed optical insulation techniques which solved most of the previous light-loss problems. The resultant glass-coated glass fibers were for many years a standard optical element for use in fiber optics. Kapany continued his work and in 1956 first applied the term "fiber optics" by defining fiber

optics as "the art of the active and passive guidance of light (rays and waveguide modes), in the ultra-violet, visible, and infrared regions of the spectrum, along transparent fibers through predetermined paths." [25]

During the ten year period from 1957 to 1967, interest and experimentation increased such that significant developments and applications were made in the following areas:

1. Waveguide mode propagation.
2. Coupling phenomenon in adjacent fibers.
3. The use of scintillating fibers for tracking high energy particles.
4. Skew ray propagation along fibers.
5. The use of fiber optics as field flatteners, Focons, and image dissectors in ultra-high-speed photography.
6. Extension of the spectral range of fiber optics in the infrared region.
7. Combining the field of lasers and fiber optics in lasing fibers, fiber amplifiers, hair trigger operation in fiber lasers, and light switching by waveguide "beating."
8. Application of fiber optics to various photo-electronics devices, data processing, and photo-copying systems. In this field of photoelectronics

alone, fiber optics have been applied in multi-stage image intensifier coupling, high resolution cathode ray tubes, end window vidicons, and various forms of scan converters.

9. Application of fiber optics to the field of medicine: cardiac catheter assemblies to record and observe oxygen saturation of the blood; application of fiber-optic endoscopes for application to gastroscopy, bronchoscopy, rectroscopy, and cystoscopy; hypodermic probes; in vivo cardiac oximeter; laser coagulator for treatment of remote tissues using fiberscopes; scintillating fibers for radiology; endoscopes for the inspection of the pericardium, thoracic cavity, bone joints, living fetus and peritoneal cavity. [25] [36]

However, before 1967, in the field of electronics, glass fibers were not seriously considered as a communications medium for transmission over even moderate distances (about 1 km) because of high attenuation losses associated with glass fibers.* Primary emphasis prior to 1968 was on image transmission devices of short length ($\ll$ 5m) and illumination devices.

---

*Attenuation, or loss of light in a glass fiber, is expressed in terms of decibels per kilometer (dB/km). This subject will be discussed in more detail in Section III.

The first serious interest for communications was expressed by K.C. Kao of Standard Telecommunications Laboratories in England in 1968. At that time, technology was paced by the ability of industry to draw fibers of long length and low loss. [32]

In 1967-68, laboratories began development programs to develop low-loss fiber optics in response to inquiries from telecommunications laboratories. An attenuation level of 20 dB/km was set as an acceptable goal (Figure II-1), since that level of performance was believed to be compatible with existing telecommunication systems configurations and would be sufficient to tip the economic scales in favor of optical waveguides. [8]

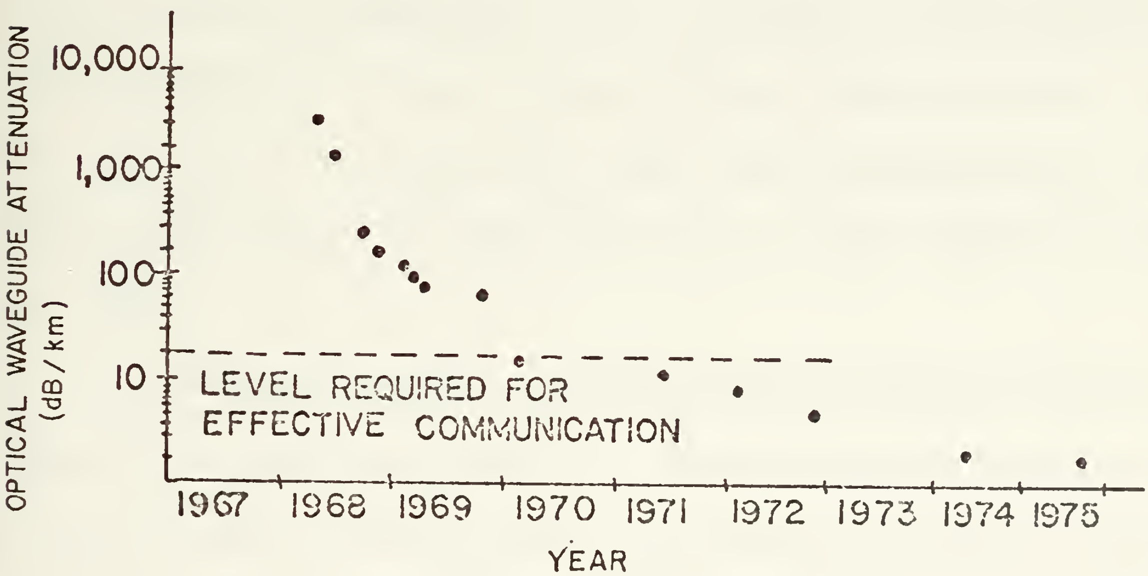


Figure II-1 Historical progress in low-loss waveguides: lowest attenuation achieved vs. year

At that time the fiber optic communication technology, involving multimode fiber optic bundles and discrete semi-conductor sources (light-emitting diodes, LEDs) and detectors (silicon positive intrinsic-negative diodes, PINs), received great stimulation and impetus from the announcement in November 1970 by Corning Glass Works of glass-fiber waveguides with 20 dB/km attenuation at a wavelength of 820 nanometers (nm). (Commercial-grade fibers up to that time had about 1000 dB/km attenuation). In 1971, Bell Laboratories developed liquid-core low-loss fibers with losses less than 20 dB/km out to 1100 nm. [35]

In August, 1972, the Corning Glass Works announced that they had surpassed the attenuation goals by developing fibers with an attenuation loss of 4 dB/km at wavelengths of 850 and 1060 nm. Losses between 600 and 900 nm were all below 12 dB/km. [8] By August 1974, Bell Labs had developed a fiber-optic cable with an attenuation loss of only 2 dB/km at 1060 nm. [6]

The development of low-loss fibers was not the only obstacle to overcome, however. Even the mundane problems of making connectors that worked and figuring out ways to repair a broken fiber in the field looked like serious roadblocks. There were so many problems as late at 1972 that few expected fiber-optic systems to find anything but specialized applications

until the 1990s. However, most of the earlier problems have been under parallel attack in dozens of laboratories around the world, most notably in Russia, Japan and western European countries. The stumbling blocks of 18 months ago have virtually disappeared. "This is one of the fastest-moving technologies I've ever seen," says Don Alexander, who monitors cable developments from International Telephone & Telegraph Corp.'s headquarters in New York. [26]

"A lot of things have come to pass in one and a half years instead of five," agrees Herbert A. Elion of Arthur D. Little, Inc., who has been working on optoelectronics since 1968. Elion, who has been working on fiber optics with a group of 27 clients from four continents -- both companies and government agencies -- says that spending for development efforts in fiber-optic systems topped $100 million in the past year (1974). He expects it to double in 1975-76. "People argue about the time scale," he says. "Some projects have been advanced from 1979 to 1976." [26]

Technologically, it appeared that it was feasible to use fiber optics in communication and data link systems. With unlimited potential for future application and the door already cracked, it only remained for both industry and the military to expend time, effort and money in research and development programs in order to start reaping the benefits offered by fiber optics.

2. Background of NELC A-7 ALOFT Demonstration Program

Man has employed optical means in military communications since ancient times. Early writers, such as the Greek historian Polybius (c. 205-125 B.C.), refer to the employment of visual signaling, including flags and smoke signals. Flag and light codes for naval communications were developed by sea forces during the sixteenth century. In 1875, the U.S. Navy began experimenting with electric lights for signaling. By 1916, Rankine had patented a voice communicator utilizing a vibrating mirror to modulate the optical carrier. The Navy developed a cesium vapor lamp which could be amplitude-modulated electrically at voice frequencies in 1944. Despite considerable effort and ingenuity, however, practical systems were limited to audio bandwidths until about 1961. By 1970, three advances of potential significance were reported: the development of the first injection laser which operated continuously at room temperature, the development of the first continuously operating dye laser, and the production of the first low-loss fiber optics transmission lines. These, and other electro-optical advances, such as light emitting diodes (LEDs), helped set the stage for fiber-optic communications systems. [33]

While visiting England in 1970, Dr. John M. Hood, a former student of H.H. Hopkins, recognized the suitability and timeliness of fiber-optic techniques for naval and military

applications. Upon his return from England, he was instrumental in having a Fiber Optics group established in the Electromagnetics Technology Department at NELC. The group, funded by internal research and development funds, was dedicated to the development of a practical technology for meeting the problems arising from the specific uses that fiber optics offers to the Navy. It was clear that a natural and obvious application was to improve the internal data links of military aircraft. It was also recognized that the potential for shipboard use was just as great. By mid-1971, various agencies of the Department of Defense (ONR, ARPA, NAVELEX and NAVAIR) had committed funds for continuing fiber-optic research. In April 1973, a Fiber Optics Development Plan was promulgated at NELC, setting forth a program for identifying and meeting the Navy's needs in the fiber optics field. This plan then became the official NAVAIR-NAVELEX development plan. It has since been superseded by the proposed DOD Tri-Service Technical Application Area Plan for Fiber Optics Communications Technology, dated 25 March 1975. At the time of this writing, the plan has been agreed to at the working level but not yet approved at the command level. [14]

In January 1973, NELC entered into a contract with the Federal Systems Division of IBM Corporation under contract number N00123-73-C-1665 for the design, fabrication and

laboratory testing of a high speed, multiplex fiber-optic data link to interconnect the tactical computer and head-up display from an A-7 aircraft. The work was performed at the IBM Electronics Systems Center at Owego, New York, during the period February to May, 1973. The final report was completed in June 1973 by H.C. Farrell and R.N. Jackson. [14] In particular, the tests, made on the link between the ASN-91 computer and the Head-Up Display (HUD) took the form of performance comparisons between the fiber-optic link and the original conventional shielded wire cable, as well as experiments on special properties of the optical link. The results were conclusive: in a noise-free environment there was no detectible difference in performance between the two types of interfaces; in the presence of an electrical noise generator, however, the output display was unaffected when the signal was received via the optical channel, but it incurred serious deterioration when the shielded cable was used. Part of the laboratory tests in this contract tested the link through the full requirements of MIL-STD-461 and MIL-STD-462 (military standard specifications on Electromagnetic Interference (EMI) and Radio Frequency Interference (RFI). These tests results were the first quantitative validation that fiber optics were definitely immune to RFI and EMI. [14]

The results of the IBM tests were made known to program review officials in the Navy Department and the Department of Defense. These officials recognized the need of a major feasibility demonstration to design and implement fiber-optic links at a full scale system level for test and evaluation. At this time, NELC made a proposal to Commander, Naval Air Systems Command (NAVAIR), for a two year program to install fiber optics in place of standard twisted-pair and coax cabling in the navigation/weapons delivery system (N/WDS) of an A-7 aircraft for test demonstration and evaluation purposes. Subsequent to this request, Dr. Malcolm R. Currie, Director of Defense Research and Engineering, submitted a memo, dated 6 August 1973, to the Assistant Secretary of the Navy for Research and Development in which he expressed confidence in the role of fiber optics technology for naval applications and thereby urged prosecution of a program for exploiting it. [12]

This request culminated in approval by the Assistant Secretary of the Navy for Research and Development and subsequent funding-go-ahead by OPNAV 982 and AIR360 for the implementation of the A-7 Airborne Light Optical Fiber Technology (ALOFT) Demonstration. The project was initially funded in March 1974 under AIRTASK A360360G/003C/4W41X1-001. [14]

In July 1974, the Chief of Naval Material, assigned the Naval Air Systems Command lead responsibility through

FY 1976 for the development of the fiber optics technology to fulfill military systems needs and applications. Commencing in FY 1977, the Naval Electronics Systems Command is designated to assume lead responsibility of the fiber optics development program. [11]

3. NELC A-7 ALOFT Demonstration Approach

As soon as the AIRTASK was received by NELC in March 1974 to initiate the ALOFT Project, NELC managers and engineers consolidated plans and objectives into a formalized Development Approach. The project was to consist of a two-year program with a milestone schedule as outlined in Figure II-2. The major project phases were as follows:

(1) A six-month system analysis and design effort to be performed in part under NELC contracts to define the system performance requirements, to design the system, and to provide a system installation plan.

(2) A six-month contractual effort to fabricate and checkout the demonstration system in the contractor's system integration laboratory.

(3) A three-month test and evaluation program of the demonstration system while installed in an A-7 ground simulator.

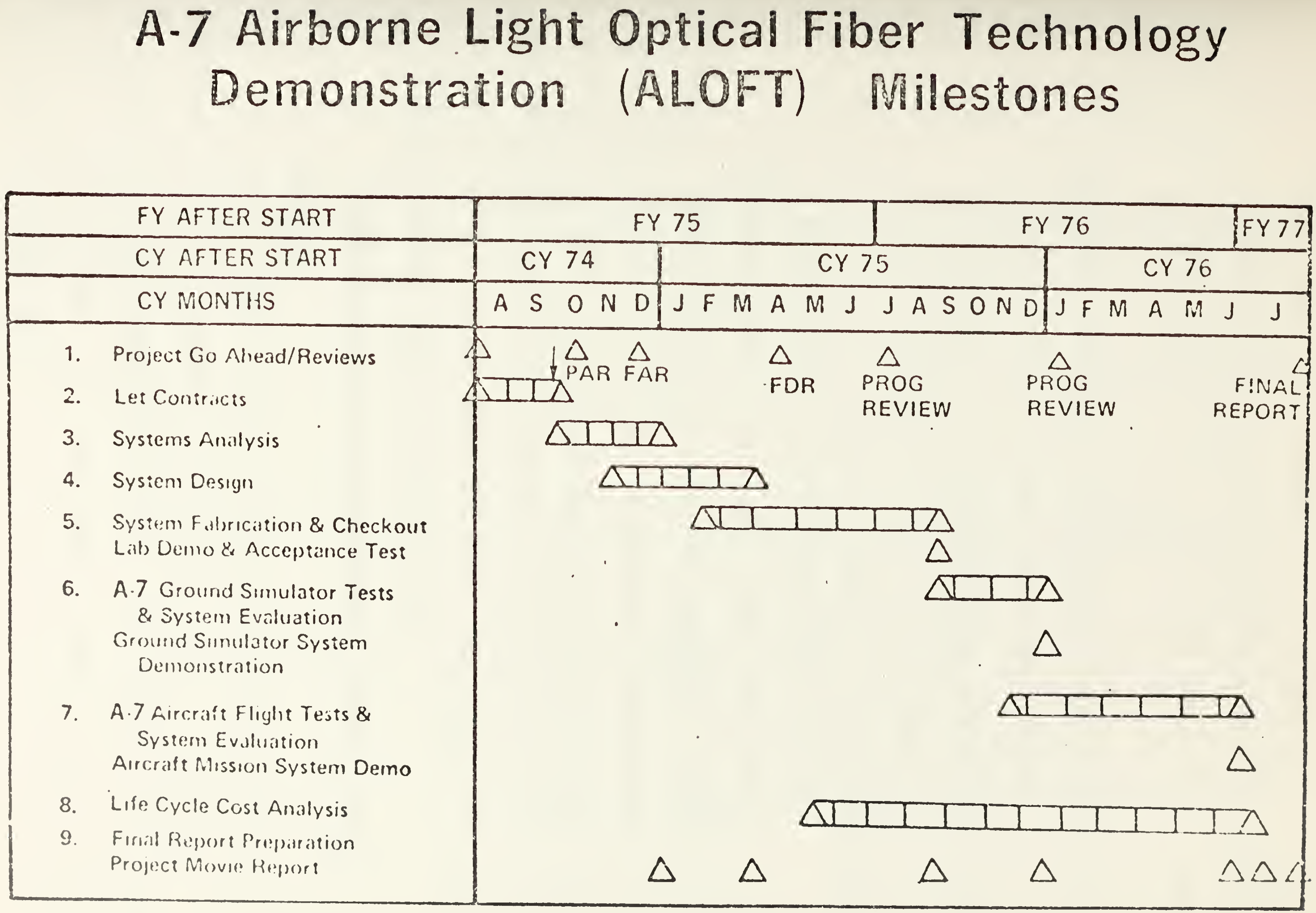


Figure II-2 A-7 ALOFT Demonstration milestones

(4) An eight-month test and evaluation phase of the demonstration system including aircraft modification, ground check, and flight test while installed in an A-7 test aircraft.

(5) Funds permitting, an economic analysis is to be performed concurrently with the checkout, test and evaluation of the demonstration system; the objective of which will be to analyze the comparative cost and performance benefits of the fiber-optic system versus a wire interconnect system.

The possibility of utilizing Naval Postgraduate School students' theses efforts to conduct independent research and give complimentary support to the economic analysis was first discussed by NPS students and NELC (Code 1640) in early 1974. The resulting proposals of theses investigations in this area proved desirable to both NELC and NPS. See Figure II-3 for A-7 ALOFT economic analysis activity flow.

4. A-7 ALOFT Demonstration Management Organizational Structure

The A-7 ALOFT project is assigned to NELC under the Aircraft Internal Communications Project Office, Code 1640. A project has been established within Code 1640 for the management of this project. The basic ALOFT organizational structure is shown in Figure II-4.

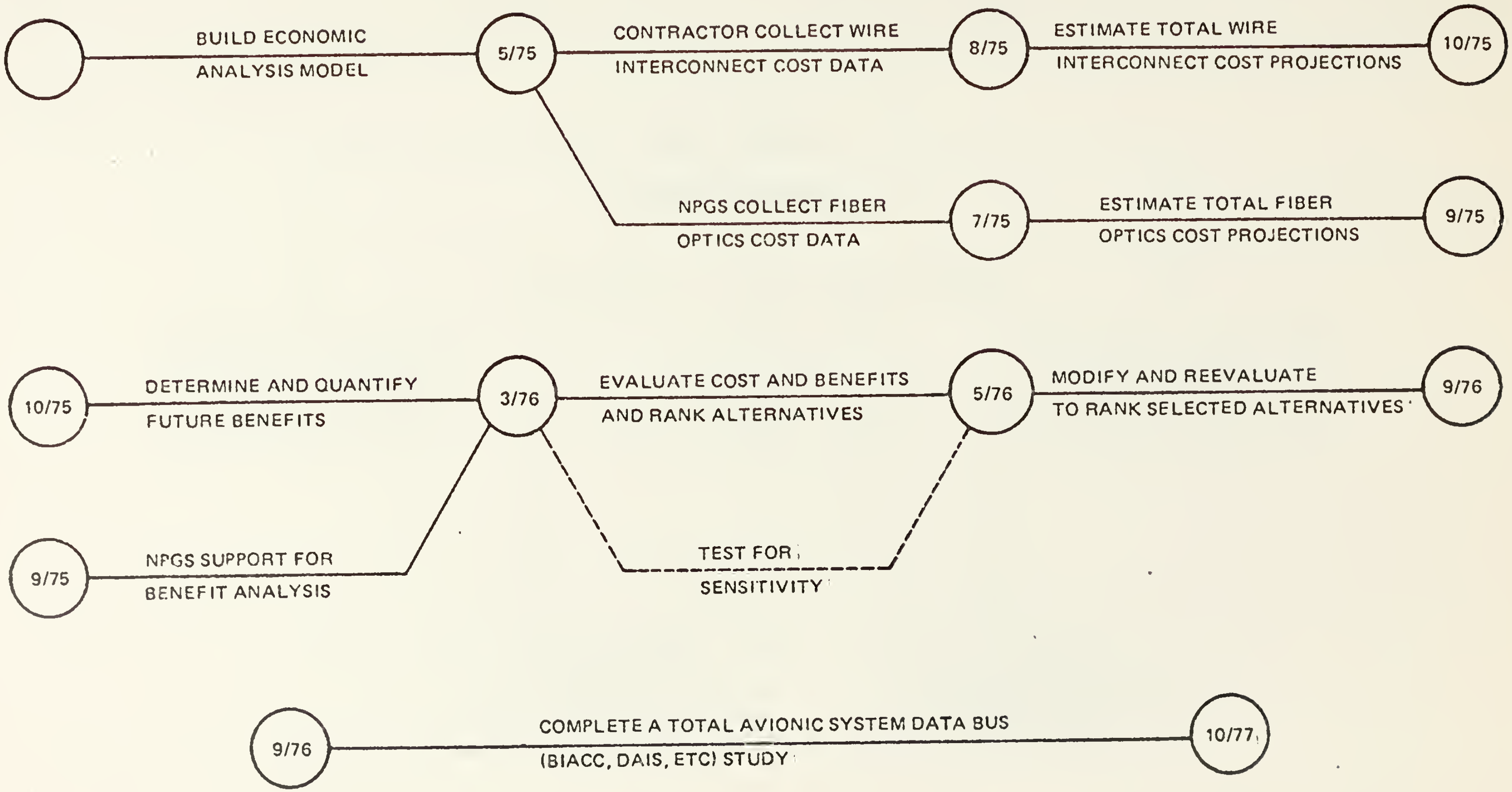


Figure II-3 A-7 ALOFT economic analysis activity flow

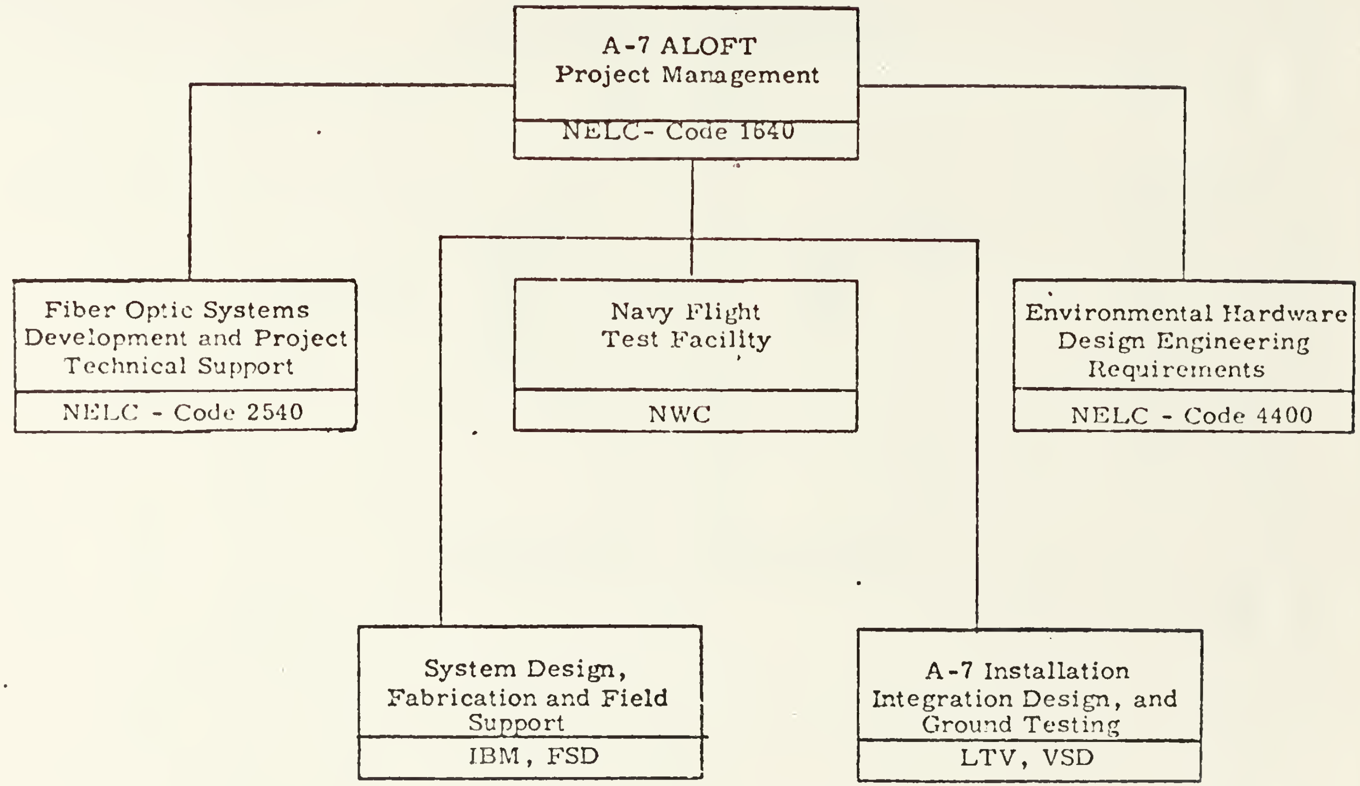


Figure II-4 A-7 ALOFT Project Office organization structure

Under the current program effort in the A-7 ALOFT project the economic analysis function will be expanded to include some in-house management along with Naval Postgraduate support and contractual assistance. This structure is shown in Figure II-5, which does not present the other organizations (see NELC-TD 369 for full organization).

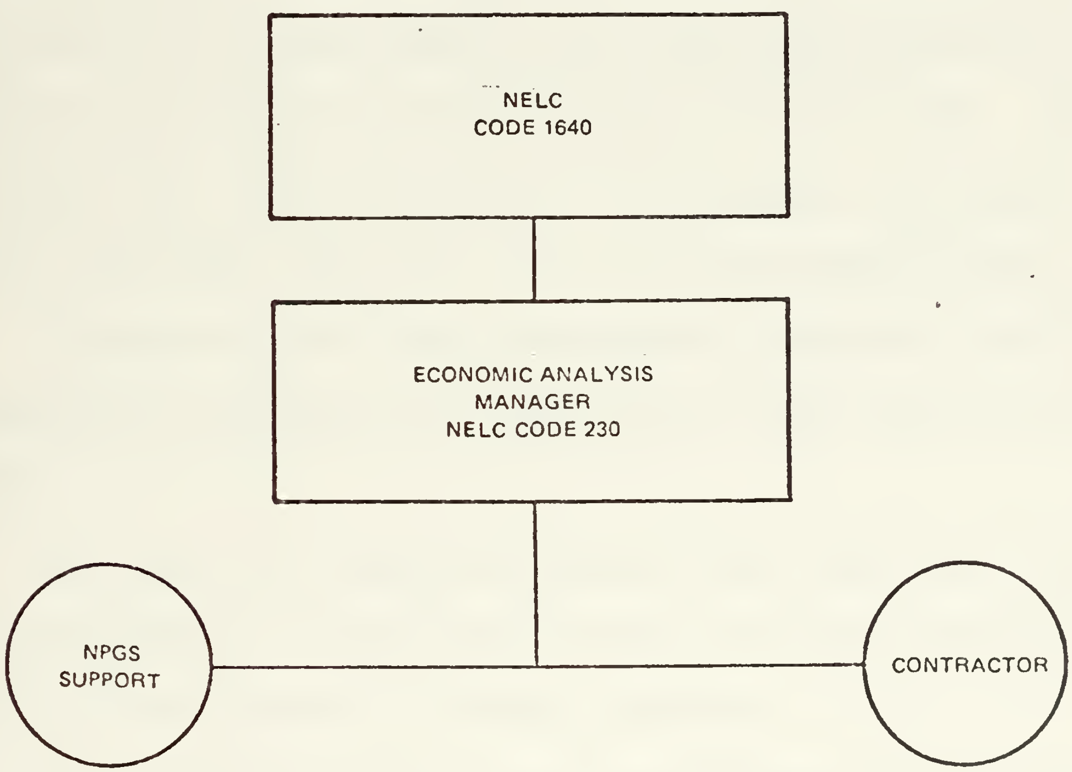


Figure II-5 A-7 ALOFT economic analysis organization structure

III. FIBER OPTICS TECHNOLOGY AS APPLIED TO DATA LINK SYSTEMS

A. GENERAL

Recent breakthroughs in fiber-optic technology have made the application of fiber-optic waveguide systems to military information transfer entirely possible and feasible. The area of avionics data transfer will possibly be the first major application or beneficiary of fiber-optic technology. Several military utilization applications have been studied and a number of feasibility demonstrations have been made. These studies have pointed up dramatic performance and potential cost advantages for a wide range of system applications.

Engineers at the Naval Electronics Laboratory Center have summarized the important properties of fiber optics as follows: [30]

(1) Cross-talk immunity between fibers and fiber cables.

(2) Security from signal leakage and tap-in attempts.

(3) No electrical grounding problems.

(4) No short circuits which could damage terminal equipment.

(5) No ringing problems.

(6) Large bandwidth for size and weight. The increase in bandwidth, combined with crosstalk/noise immunity, makes miltiplexing at high data rates possible.

(7) Small size, light weight (glass is 1/6 the weight of copper), and flexibility - thus, ease of installation.

(8) Potential low cost - when considering common factors such as size, flexibility, equivalent bandwidth, and manufacturing quantity. The strategic availability and cost of copper as compared to glass will play a future role.

(9) High temperature tolerance (500 to 1000°C).

(10) Safety in combustible areas and hazardous cargo areas (i.e., ammunition and fuel storage areas).

(11) No copper (strategic material).

(12) Potential Electromagnetic Pulse (EMP) immunity.

(13) RFI/EMI, noise immunity (glass, a dielectric, does not pick up nor radiate signal information.

B. FIBER OPTICS RELATED TECHNOLOGY

Certain principles, components and data link systems should be discussed before delving into the actual components used in the A-7 ALOFT project. This discussion is necessary for a greater understanding of a multiplexed fiber-optic system as a whole.

1. Attenuation

Light is attenuated as it moves down an optical fiber. Light is lost both to absorption and scattering in the fiber.

The absorption is determined primarily from the bulk of the glass from which the fiber is made. It converts light into heat. The scattering is due both to the bulk material and to fiber manufacturing defects. Radiation losses can also occur because of bends in the fiber, but losses are not significant unless bends are below a minimum bending radius.

Attenuation is a primary factor in the economics of fiber optics communication systems. It determines a system's repeater spacing, source output and detector sensitivity.

Attenuation can be measured in decibels because of the exponential nature of light attenuation in a fiber as given by:

$$P_o = P_i e^{-\alpha L}$$

where

P_o = power at receiving end of fiber

P_i = input power

α = extinction coefficient

L = fiber length

Extinction coefficients are sometimes used but decibels have become the accepted measure of attenuation.

$$\text{Attenuation (dB)} = 10 \log \frac{P_i}{P_o}$$

$$P_o = \frac{P_i}{10^{\,dB/10}}$$

The graph in Figure III-1 shows how a low-loss fiber's attenuation changes with the wavelength used. It was obtained by Corning Glass researchers using one of their 4 dB/km low-loss fibers. [3]

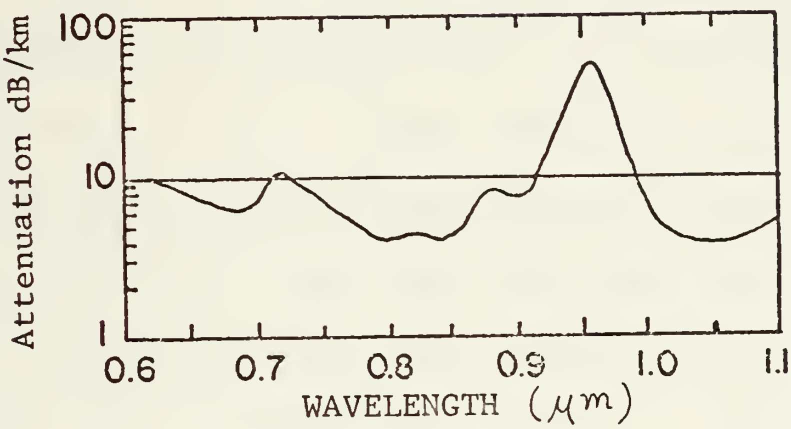


Figure III-1 Attenuation as a function of wavelength in a recent Corning low-loss optical fiber

2. <u>Modulation</u>

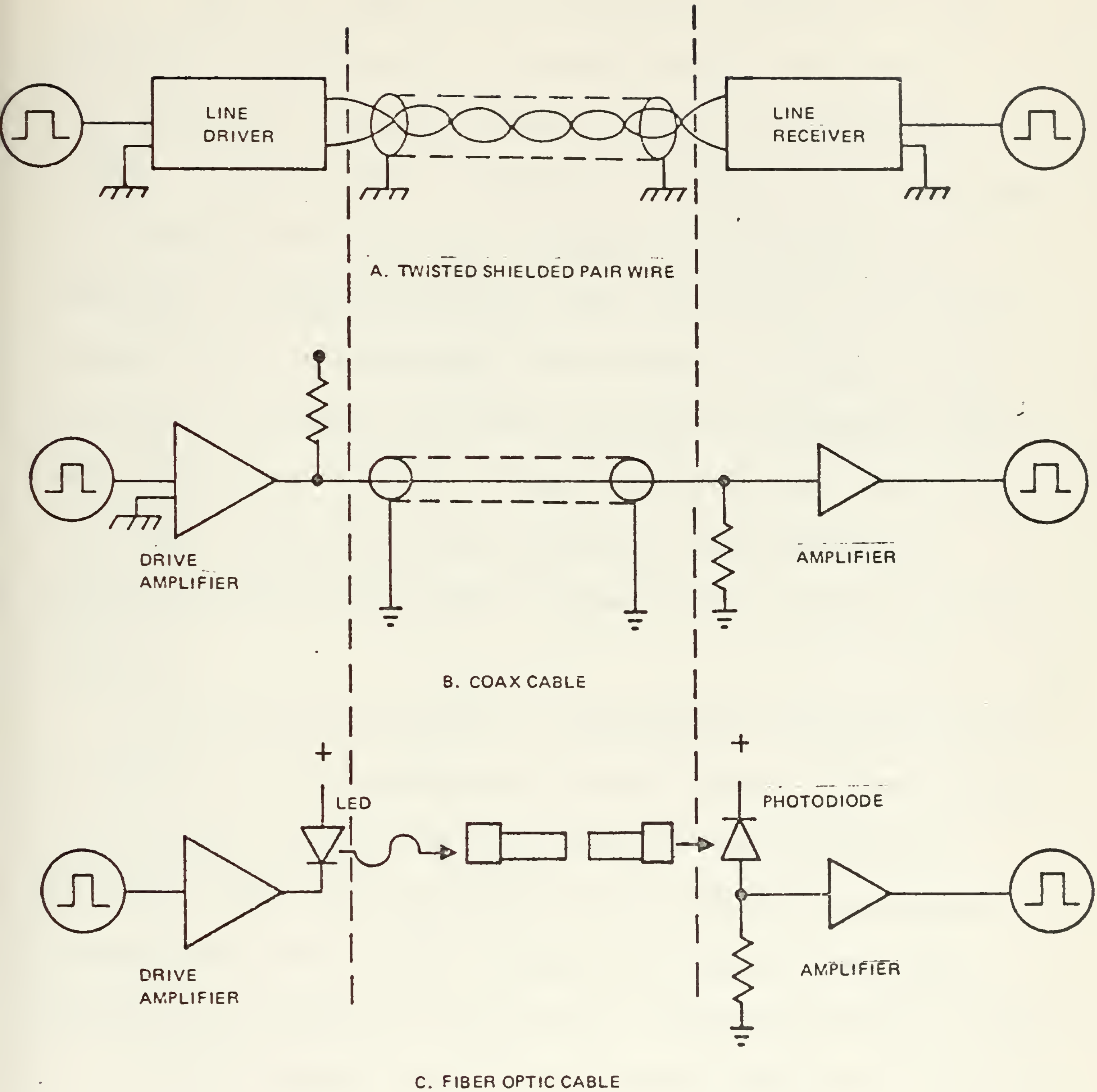
Light, as a carrier signal, from a light source such as a Light Emitting Diode (LED) must be modulated in order to carry data. The traditional modulation techniques of amplitude and frequency modulation require complex electronic circuitry, sine wave sub-carriers, etc., and increase costs, as well.

Digital Transmission is the easiest modulation mode to implement with optics. This results from the approximate linearity of LEDs in which the light output varies directly to

the drive current. The digital signal can be connected to the LED input port through a driver circuit or by digitally controlling the bias current to the LED. Where used as a binary on-off keying device, this technique causes a logic 1 input to give a logic 1 light output. [2]

Figure III-2 shows a block diagram of the typical fiber-optic system using a digital signal from a LED source. The signal could be a linear signal from a laser diode as well. For high speed operation, one would use wide bandwidth amplifiers.

Modulation rates achievable with LEDs are considerably lower than those possible with semiconductor lasers because the rise times in the LED are limited by spontaneous minority carrier lifetimes, rather than stimulated minority carrier lifetimes, as in the laser. Nevertheless, very useful modulation rates are possible up to a few hundred megahertz (MHz). Assuming an acceptable fiber loss factor in the range of 50 dB/km, one finds a 200 MHz limit with fiber optics for a 300 meter length. This is primarily a function of the electro-optic devices available. Coax, on the other hand, is limited to 20 MHz for the same cable size and length, and a twisted pair wire pair to 1 MHz. [28]



Source: NELC

Figure III-2 Typical interface systems

3. Multiplexing/Data Bus

One of the basic data transmission methods naturally applicable to fiber optics is multiplexing, a well known technique which provides efficient use of a transmission medium. A large number of single-strand wires may be replaced by a single twisted pair for transmitting information, or similarly, a single fiber-optic cable may replace many single-strand wires or single-strand fiber cables. In short, multiplexing is the process of combining several information channels and transmitting them over a single communications link. The two primary methods of multiplexing are time-sharing and frequency separation, as shown schematically in Figures III-3A and III-3C.

The need to multiplex is becoming more and more evident as avionics systems become more and more complex. Some systems engineers at NELC feel that continued use of conventional approaches might not be capable of providing the information exchange required by future integrated, computer controlled multiplexed navigation, fire control, and communications systems.

Multiplexing of an avionics system configuration provides advantages in several areas: reduced weight, increased flexibility, ease of modification, ease of maintenance, reduced life cycle costs (attributed to reduced maintenance and modification, irrespective of investment costs) and a higher survivability rate. [2]

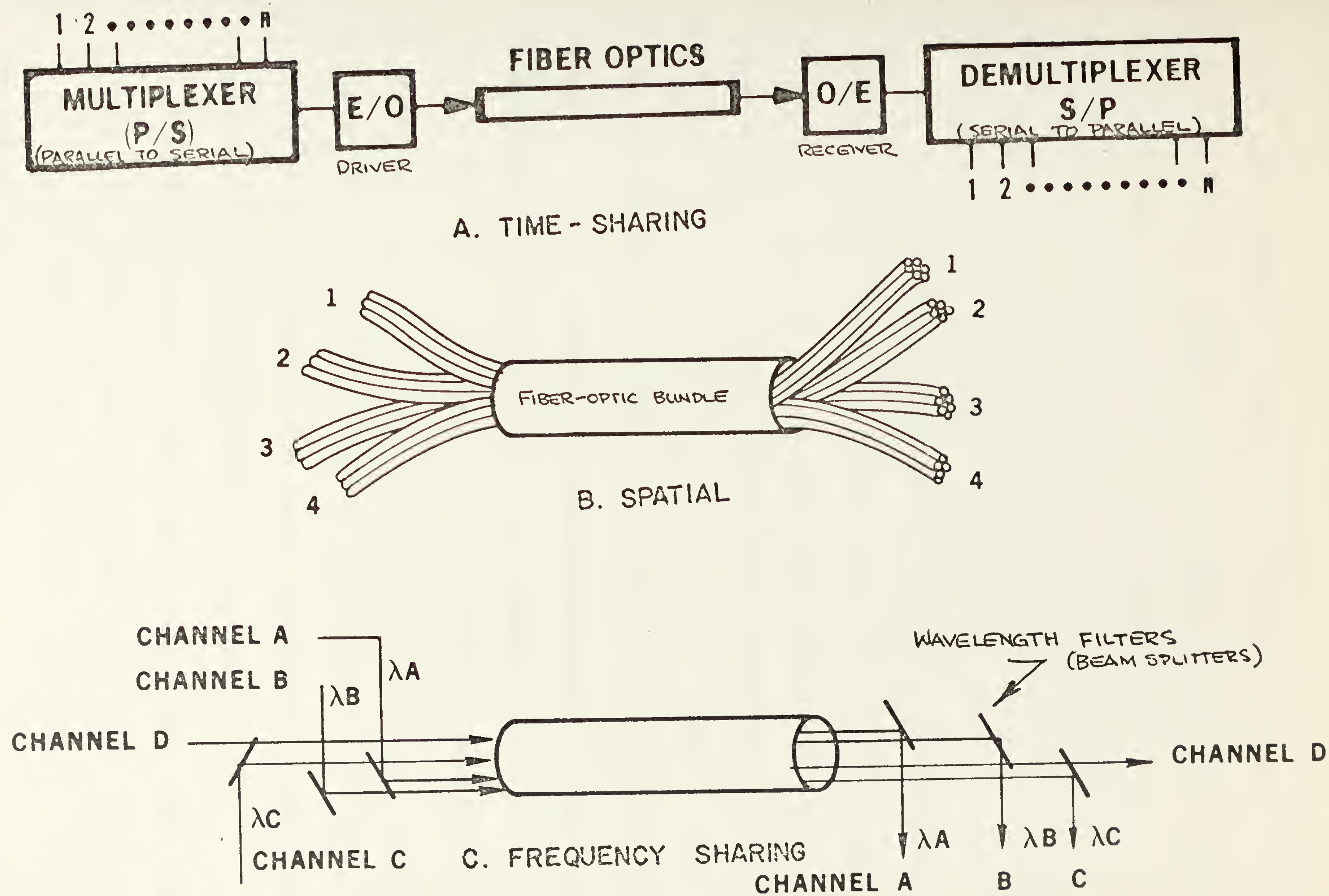


Figure III-3 Data multiplexing

NELC 401-320 SAN DIEGO

The optimum multiplexing approach is known as "data bus," in which a central control computer addresses each of several remote units in turn on a programmed basis in the time division multiplex approach (TDM), or by addressing remote units individually by suitable filtering in frequency division multiplexing (FDM). Figure III-4.

Certain avionics systems of the F-15 have been multiplexed using the data bus system, with the avionics units tied directly to the data bus through their own interface units. Among the avionics units multiplexed on the F-15 are inertial navigation set, inertial measurement set, navigation control, radar warning device, radar fire control, air data computer, heads up display and the altitude heading and reference set. Total capacity of the system is one megabit. [1]

Multiplexing on the B-1 will be more extensive. The system is designed to handle over 12,000 electrical signals which will be multiplexed into a single twisted pair wire cable. Each of three separate multiplexing systems will have a data capability rate of approximately one megabit. [13]

Fiber optics do offer certain advantages over coax/ twisted pair cables, such as increased data rate capability and better RMI/EMP immunity, but fiber optics don't offer much extra in terms of multiplexing alone. It is true that most of the advantages of multiplexing can be gained by using conventional

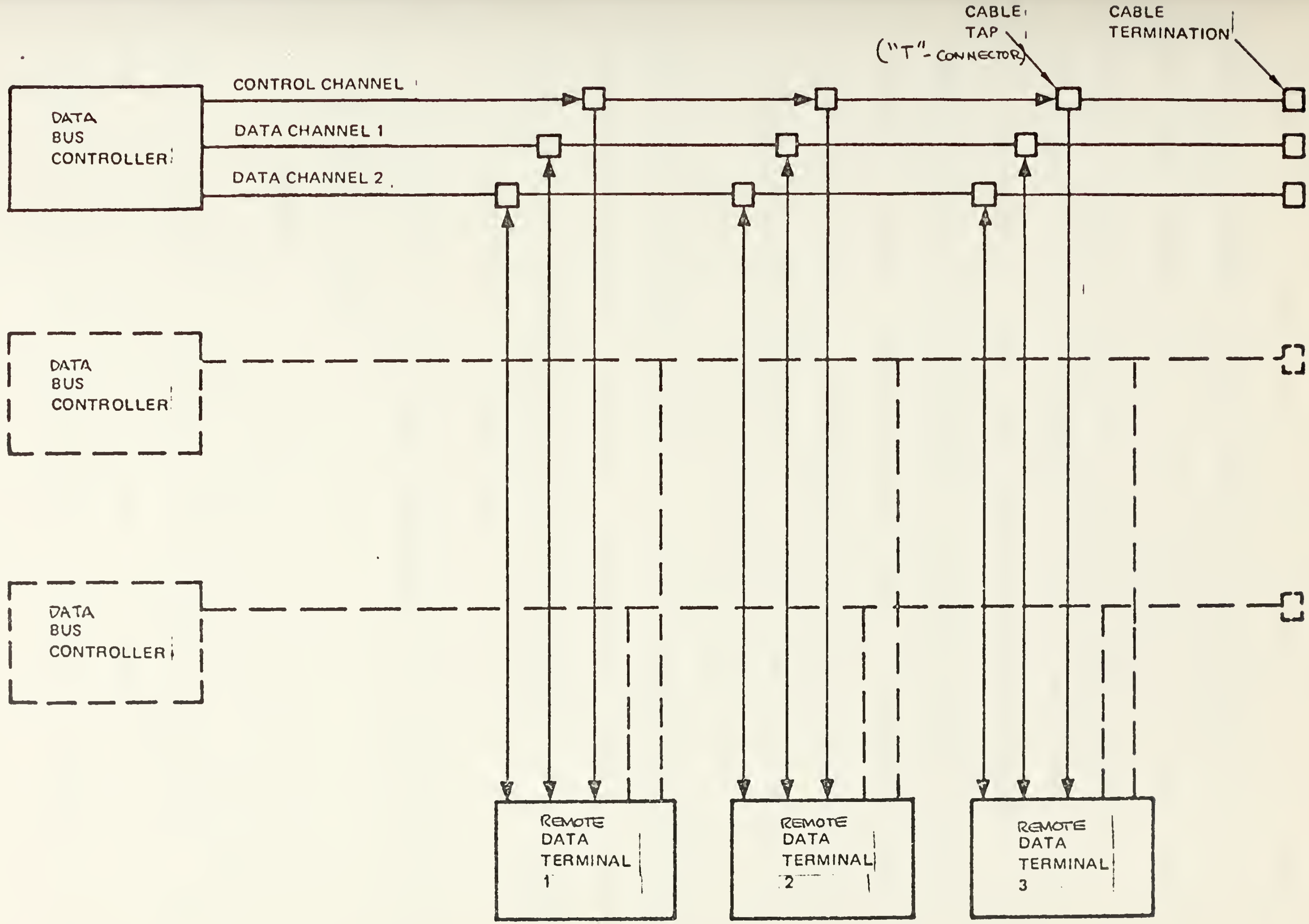


Figure III-4 Typical aircraft data bus architecture

cables. It is also true that there would not be substantial additional weight savings achieved by replacing the few remaining twisted pairs in the multiplex system with optical fibers. Present fiber-optic technology does not permit a direct one-for-one replacement of twisted pair used in the data bus concept, since fiber optic cable "T" connectors and "star" couplers (multi-terminal connector) are not readily available outside research laboratories. It would be possible to install a point-to-point system with fiber-optic cables running from each remote unit to other remote units and the central computer. Although this design would not necessarily mean size and weight savings, it could provide the EMI and EMP advantages which are even more important in a multiplex system where increased emphasis is placed on integrity of the signals being transmitted on a few wires.

C. DESCRIPTION OF THE BASIC COMPONENTS OF A FIBER OPTIC DATA TRANSFER SYSTEM

1. General

It should be kept in mind that the A-7 ALOFT Demonstration is designed to utilize "off-the-shelf" components. The short term objective is to prove the feasibility of a multiplexed electro-optic transmission system for integrated digital airborne avionics systems utilizing the A-7E as a test bed.

The system, as designed, is a demonstration only and is not envisioned as being a design prototype for future generation avionics systems. Future fiber optics avionics systems would not necessarily be designed to incorporate all or any part of the present "off-the-shelf" technology of point-to-point systems, e.g., discrete circuits, and multimode fibers. Rather it is probable that future systems would be designed to incorporate improved LED or laser injected diodes, single mode fibers, integrated optical circuits and a data bus concept, etc.

2. Glass Fibers/Cables

Light is able to propagate through glass or plastic fibers because of the well known phenomenon of Total Internal Reflection (TIR). For this phenomenon to hold true it is necessary for certain conditions to exist. First, light rays must hit the entrance end at angles less than the critical incident angle, θ_c, or otherwise be deflected from the desired course. Figure III-5. Second, the fiber itself must have met exacting manufacturing standards to prevent surface imperfections which will cause absorption and scattering of light. In particular, metal ions such as iron, nickel or cobalt -- normally used to color glass -- should be eliminated because of their light absorptive characteristics. In addition, the fiber (or fiber bundles) should be designed so as to prevent leakage of light from fiber to fiber because of cross-coupling

effects. These effects are associated with the penetration of light into the surrounding low-density medium. The penetration depth is small, reaching at most 2 λ (λ =wavelength of transmitted light). Leakage is therefore significant only in sufficiently dense fiber bundles. [27]

A light ray undergoes a multitude of reflections even when propagating along a relatively short fiber. Calculations show that in a fiber about 50 microns diameter, there are upwards of 13,000 reflections per 1 meter of fiber length. [34]

To prevent leakage of light, fibers are coated with special materials which provide a high reflection coefficient. This material is usually a dielectric coating called the outer cladding. The outer cladding has an index of refraction (n) somewhat lower than the glass core. As a result, light rays are trapped in the core by reflection from the cladding, as shown in Figure III-5. Note that the zigzag path slows arrival of some rays.

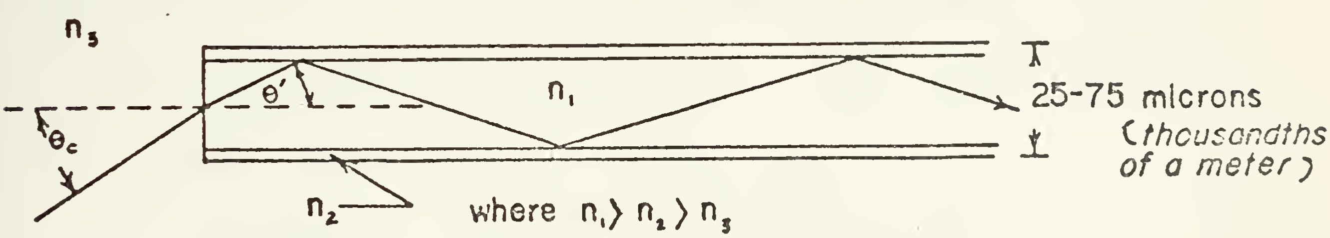


Figure III-5 Typical glass-clad fiber. The optimum sheath thickness is approximately equal to the wavelength of transferred radiation.

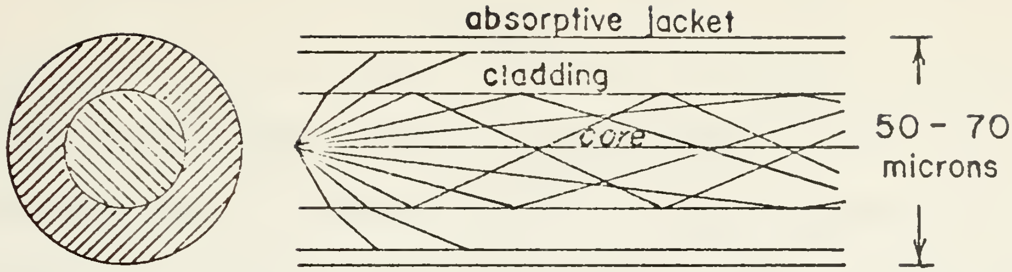


Figure III-6 Large-core, solid-clad fiber. The diameter is slightly wider than a human hair.

Light rays that graze the cladding at shallow angles are reflected back into the core resulting in a zigzag path for some rays while other rays follow essentially straight lines along the core. Figure III-6. This zigzagging can create problems in timing for long distance communications by distorting the on-off digital pulses used for high density communications. This particular problem, however, would not be a factor in short distance data link systems in aircraft.

One method of eliminating the delay problem is to make the central core so small (a few microns) that only a single ray can pass through it. Figure III-7. Such fibers are called "single mode" fibers and must be used with lasers.

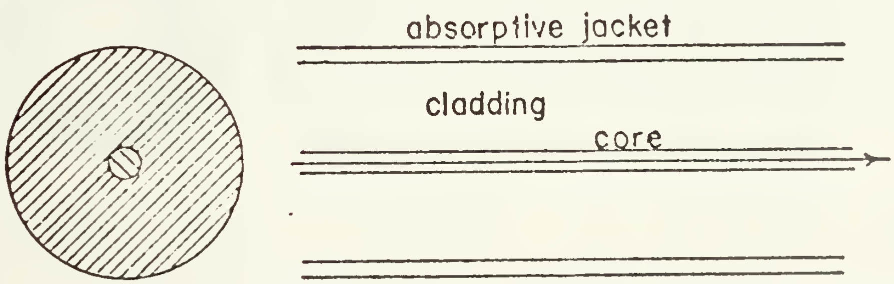


Figure III-7 Single-mode fiber. Core diameters are only a few microns, typically on the order of the light wavelength.

Transmission of a light pulse down a single fiber introduces a new set of considerations and limitations not previously encountered. Present indications are that an information rate of at least $3X10^{10}$ bits/second should be attainable in a single fiber guide over lengths of one kilometer. [35] Present techniques for utilizing single mode transmission incorporate laser-injection-diodes as a light source. However, one of the most troublesome problems is splicing (joining) two fibers together such that the signal can travel on without distortion or undue attenuation.

Graded-index fibers have an index of refraction which gradually becomes lower from the center outward. Instead of travelling in zigzag paths, light rays follow a roller-coaster-like sinusoidal path. Figure III-8. The gradually changing refractive index actually speeds up light rays travelling farther from the central axis. This results in light rays arriving at nearly the same time, even over long distances, thus minimizing "smearing" (nodal dispersion) associated with

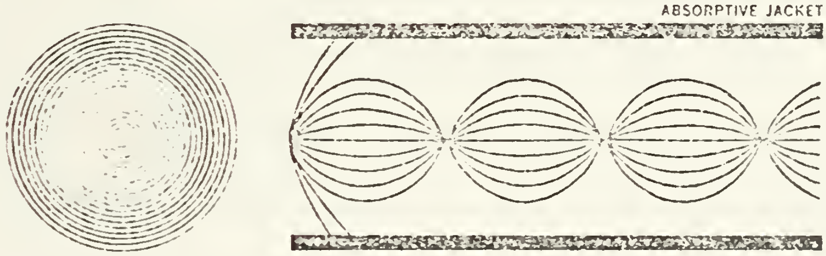


Figure III-8 Graded-index fiber. Its refractive index decrease with increasing rapidity (parabolically) from the center outward.

other fibers. The most common graded-index fiber, known as SELFOC (self-focusing), was developed by Nippon Sheet Glass Company, Ltd., of Japan.

SELFOC offers several advantages over the total internal reflection fiber including larger bandwidth with no appreciable wave form distortion, and the capacity for single fiber imaging and special multiplexing. The disadvantages are a lower flexibility than the TIR fiber due to a larger diameter and the difficulty in bundling SELFOC fibers effectively. [1]

SELFOC fibers are possible candidates for an optical data link because of their major advantage in their capability to preserve the mode pattern and the fact that the absence of a core-cladding interface eliminates the potential source of defects from impurities and scattering centers which may occur during fiber drawing. However, in the opinion of R.L. Ohlhaber of IIT Research Institute, the typical high attenuation (approximately 200 dB/km) as well as complex fabrication procedures and their associated cost all but eliminate SELFOC for long distance communication at the present time. [35]

Individual fibers may be bundled into a cable (multimode) no thicker than the lead of a pencil as shown in Figure III-9. Fiber bundles have enormous signal-carrying capacity for their size. Each fiber in the bundle, carrying signals as rapid on-off bursts of light, has the capacity for many

thousands or, theoretically, even millions of voice channels. By comparison, as pointed out in an article by Mr. John Free, 22-guage twisted-pair wire can carry 48 one-way voice channels while a coaxial cable might carry 5400 one-way channels. [18]

For most applications many fibers must be bundled together to couple them efficiently to available light sources and to provide redundancy against broken fibers. For cylindrical fibers, the closest possible bundling arrangement is hexagonal. Due to the empty spaces between fibers in a bundle, only a fraction (the so-called packing fraction) of the total bundle area is capable of accepting light for transmission. This fraction must be accounted for in designing applications requiring a minimum light transmission for detection.

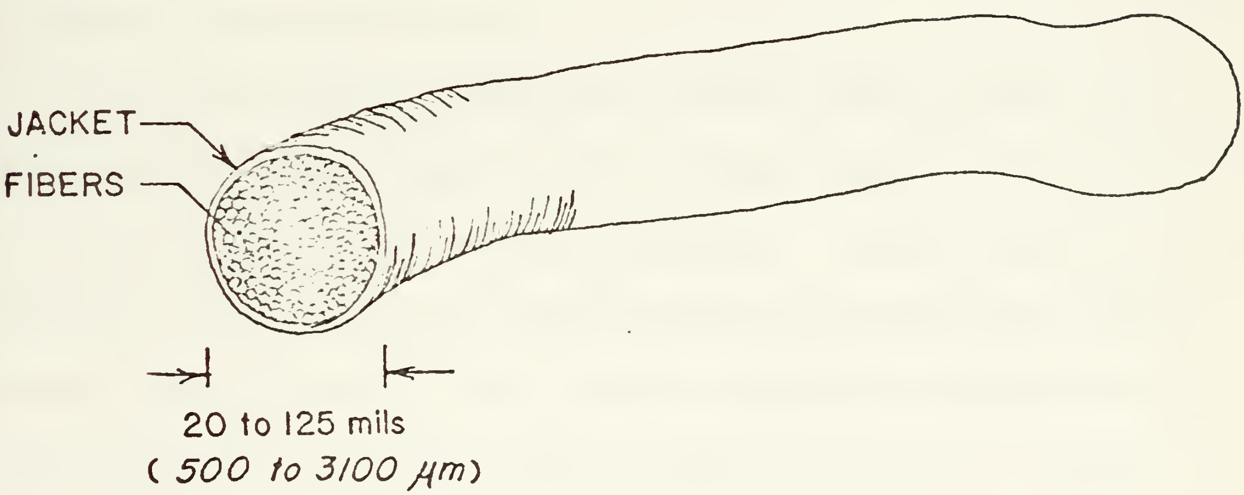


Figure III-9 Fiber-optic bundle

Thirteen fiber-optic cables (multi-mode) are to be used in a point-to-point system application of the A-7 ALOFT Demonstration. The A-7 ALOFT Fiber-Optic Interface System Components Requirements call for a cable composed of 367 fibers, each fiber having a diameter of 0.00215 inches. See Appendix C. The cables are to be covered with a non-metallic jacket and shield which is non-toxic upon decomposition. Such a jacket might well be made of an improved dielectric plastic polymer compound such as "Hytrel." Extruded Hytrel tubing, made by Valtec Corporation, is completely flexible yet exhibits crush-proof characteristics. [14] Polyvinylchloride (PVC), an early candidate for protective cabling, has been eliminated as a candidate for protective cabling material because of its toxicity upon burning and its poor mechanical characteristics at high or low temperatures.

The fiber-optic cables for the A-7 ALOFT program are of the medium loss category, with a maximum optical attenuation of 590 dB/km at 910 nanometers wavelength. Cables with such attenuation characteristics would hardly be suitable for long distance communication links, but are completely suitable for relatively short distances aboard ships or aircraft. Cables with light losses of 350 dB/km means that half of the signal is lost in less than 10 meters, half of the remaining signal within the next 10 meters and so on. That's an enormous loss,

but even so, enough light emerges at the end so receivers can accurately decode the transmitted signals.

Long distance communications would require a lower loss cable (i.e., less than 20 dB/km) as well as repeaters. For example, if the one or two dB/km fibers developed by Bell and Corning Labs were used, repeaters would be spaced every 10 miles. That's better than current wire and coaxial cables, which require a repeater every few (approximately 4) miles. [18]

Current fiber-optic cables being used in the A-7 ALOFT project were supplied by Valtec Corp. Two hundred twenty-four feet of this fiber optic cable is used on a straight point-to-point system for ALOFT. It should be noted that transmission requirements in the ALOFT system configuration could have been met by 13 coaxial cables utilizing 224 feet of RG-316 coaxial cable -- but only at the expense of increased EMI/RFI susceptibility and with a slight increase in weight. [14]

3. <u>Connectors/Couplers</u>

a. Connectors

With any fiber-optic system there is always the problem of connecting the fiber-optic cable at either end to a light source and a data receiver. The fiber surface at either end must be rigidly held in position. The ends are polished and anti-reflection coatings are sometimes added in order to reduce attenuation. In the case of the connector at the source

end, it must be positioned such that a majority of the light from the source falls within the acceptance angle of the cable. Figure III-10. In the case of detector coupling, the detector surface must be large enough to collect the spreading output light.

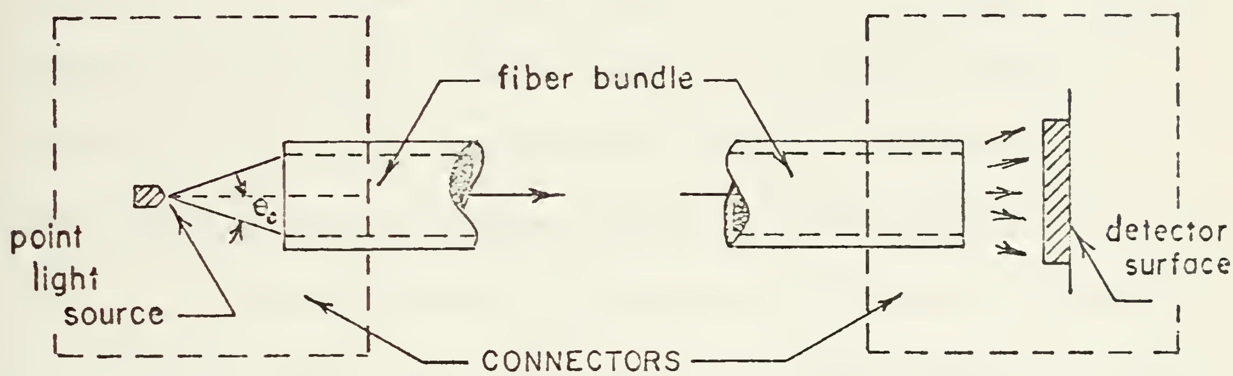


Figure III-10 Multimode cable connectors

A single mode fiber, offering bandwidths up to 10^{11} Hertz, requires critical source alignment with a laser source because of its small size and small numerical aperture. Numerical aperture, NA, is defined as a measure of the light gathering capacity of the fiber:

$$NA = n_o \sin \theta_c$$

where n_o is the refractive index of the material outside the fiber and θ_c is the incident angle of the light ray.

Multimode fibers offering a bandwidth of 10^8 Hertz can be very easily coupled to multimode emitters (e.g., Light Emitting Diodes), which operate at low power and are more

efficient. They are also less expensive than a laser source. Low power operation and efficiency are intrinsic properties of LEDs -- not causes for the lower costs. The basic problem of LED-to-fiber and fiber-to-detector couplers is to maintain the proper geometry for efficient coupling. Extremely close tolerances other than concentricity are not required. Simple machined housings and epoxy cements are proving adequate. Sealectro Corporation has supplied NELC with hermetically sealing connectors of the type shown in Figure III-12.

Simple machined housings are all that is required of multimode fiber-optic connectors. By comparison, stringent capacitive and inductive design requirements of electrical connectors cause housings to be more complicated. Often, parts must be gold-plated in order to satisfy these design requirements.

The problem is not simple when considering multichannel connectors. ITT-Cannon Corporation had to tackle that problem in order to design and build a 13-channel bulkhead connector for IBM to mount in the wall of the A-7 computer. Five prototypes were sold to IBM. One was delivered to NELC. The development of this connector is undoubtedly of importance, as explained by Mr. Anderson of Galileo Corp. when he says, "The development of this connector could be among the most important developments of the entire program (ALOFT Demonstration)." [18]

Little information is available on single fiber connectors. Alignment of the microscopic size core of a fiber with a source or detector surface can be critical. Present methods normally involve imbedding fibers in a substrate material or using epoxy cement as a binding agent to hold the fiber in alignment. The Deutsch Company developed a mechanical single mode connector for Corning in mid-1975, but further information was not available to the authors.

One of the biggest problems of interconnecting fiber optics involves the question of just where to make the connections. Some feel that the LED-fiber interface is the most obvious interconnection point while others feel that the critical nature of the optical interface will prevent making the connection at that point. NELC has considered three basic approaches to the problem. Figure III-13. They have decided that for the present, the optical interface has several advantages over other proposed fiber-optic interface methods:

(1) Elimination of contact discontinuity at the "break point" because of the optical coupling instead of electrical contact. This eliminates such connector problems such as oxidized contacts, mechanical reliability (bent pints), etc.

(2) Throw-away modularity. The electronic circuitry, LEDs, etc., could be replaced if either failure occurs or technology advances necessitate updates.

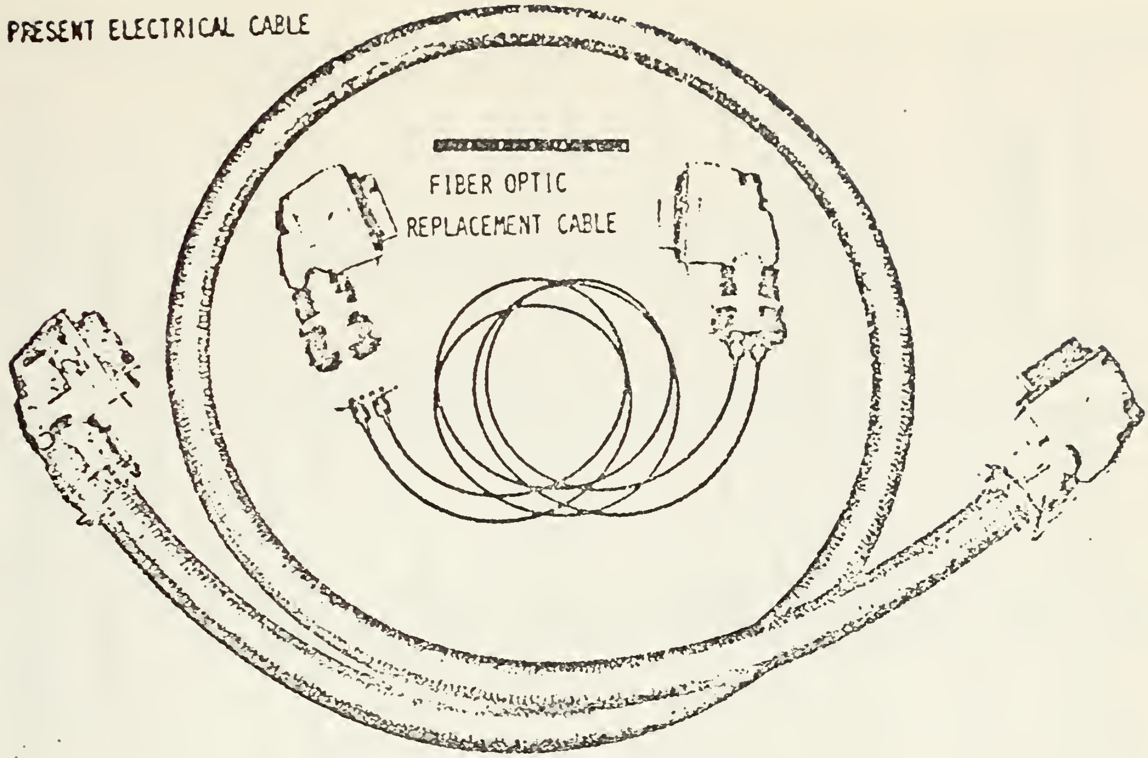
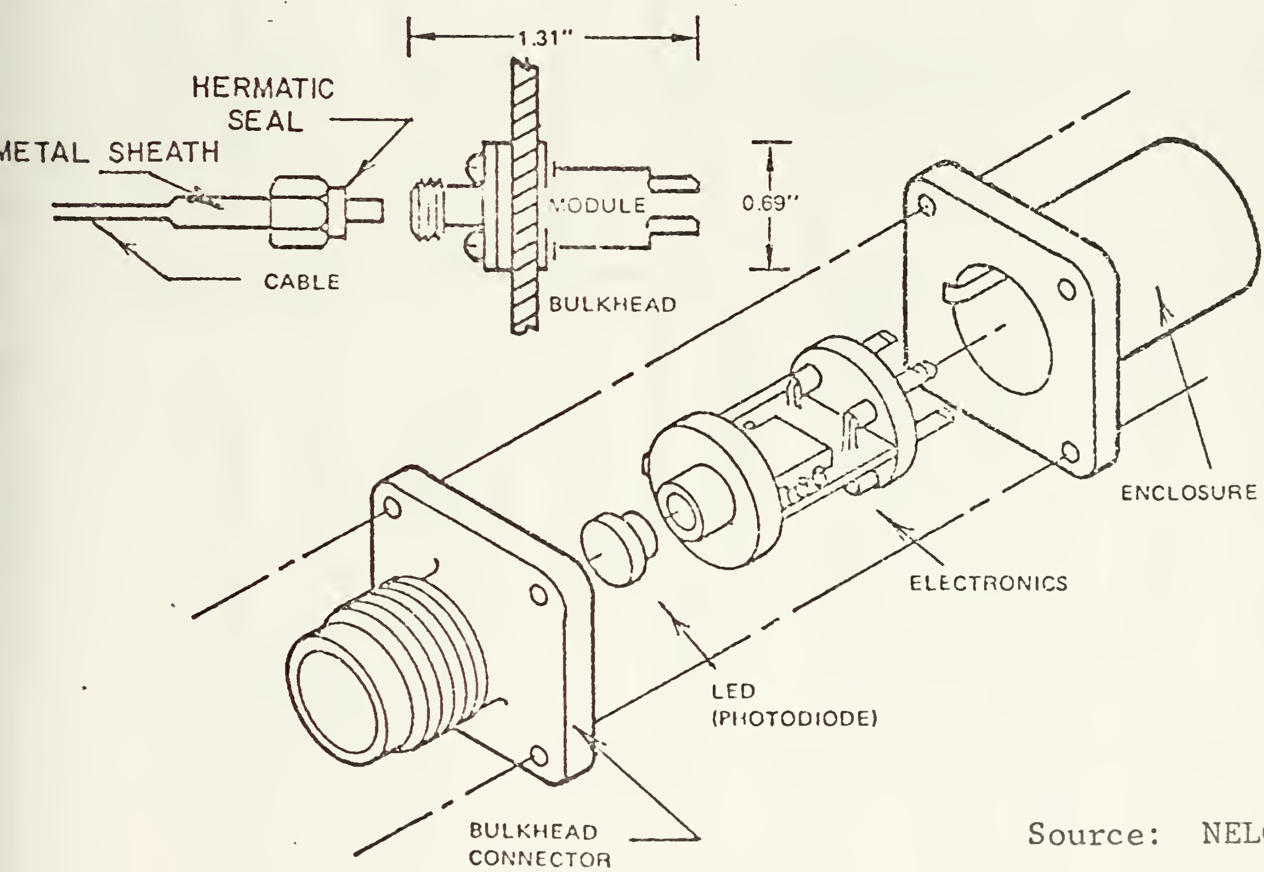


Figure III-11 Typical fiber-optic link replacement.



Source: NELC

Figure III-12 Standard package -- fiber-optic module

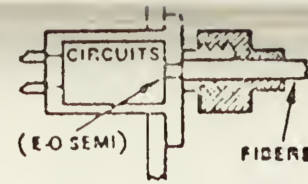
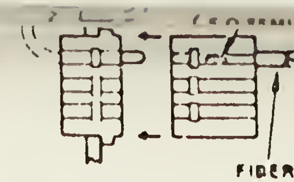
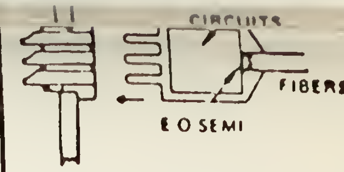
BASIC APPROACHES →	 A. OPTICAL INTERFACE	 B. ELECTRICAL INTERFACE—1	 C. ELECTRICAL INTERFACE—2
USES EXISTING OR MODIFIED ELECTRONIC CONNECTOR HARDWARE	YES, MODIFIED (BOTH)	YES, MODIFIED (HALF)	YES, MODIFIED (HALF)
ELECTRICAL PIN CONTACT DISCONTINUITY PROBLEMS ELIMINATED	YES	NO	NO
FIELD TERMINATION OF CABLE ASSEMBLIES	YES	YES	NO
EMI EMP AT CIRCUIT/E—O SEMICONDUCTOR INTERFACE	YES	NO	YES
FACTORY OPTIMIZED CIRCUIT/E—O SEMI. COMPATIBILITY	YES	NO	YES
THROW AWAY MODULARITY	YES	YES	NO
CIRCUITS AND E O SEMI. IN SAME ENVIRONMENT TRACKING TEMP	YES	NO	YES
SYSTEM LEVEL DEVICE NO CIRCUIT DESIGN REQUIRED	YES	NO	YES
OPTIMUM HEAT DISSIPATION TO BULKHEAD MOUNTING	YES	NO	NO
MIL STD 461 & MIL STD 462 QUALIFIED	YES	NO	NO
IMMUNITY TO ADJACENT CHANNEL CROSSTALK	YES	NO	YES
INTERFACES DIRECTLY WITH STANDARD DIGITAL/LINEAR FORMATS	YES	NO	YES
FIBER OPTIC CABLE CONTINUITY TEST WITHOUT SPECIAL TOOLING	YES	NO	NO TEST POSSIBLE
MATES WITH FIBER OPTIC PRESSURE BULKHEAD PENETRATOR	YES	NO	NO

Figure III-13 Basic approaches to interfaces

(3) Diode-circuit matching and engineering is no longer the systems designers' problem.

(4) Easy to install and replace.

b. Couplers for Data Bus Applications

The concept of the data bus is becoming increasingly evident in the design of new generation aircraft. A data bus system is potentially less expensive to install and maintain, lighter in weight and smaller in size, more reliable, easier to modify and expand, and less vulnerable to damage than systems based on point-to-point links.

If fiber optics are to be considered as viable replacements for electrical lines in data bus systems of the future, properly designed couplers, junctions, and terminations must be perfected.

Successful laboratory models of both single-access Trunk Couplers (T-couplers) and multi-access (star) couplers have been tested at NELC. It was concluded that star couplers make it possible to implement a data bus with a large number of terminals without a repeater. If a system using "T" access couplers is used, a repeater is necessary if there are more than ten terminals. It was concluded that the information flow requirements of a modern military aircraft can be met using either access couplers or star couplers. [38] If the number of

terminals is large, resulting in unacceptable attenuation levels, a repeater would be required in an access coupler system.

4. Light Sources/Signal Drivers

Various types of light sources can be coupled to fiber optics for useful purposes. For instance, typical tungsten filament lamps, bulbs and other common light sources are used in connection with fiber optics in market areas which include TV, stereo and appliance illumination, gas and electric burner pilot light indication, dashboard and cockpit instrumentation lighting, medical endoscopes, etc., and monitoring of remote light sources. However, for communication purposes, only the semiconductor laser and the light emitting diode appear attractive for interconnections on aircraft and spacecraft.

The signal driver for the A-7 ALOFT Project utilizes a discrete circuit driver-amplifier with LEDs, resistors, capacitors, and integrated circuit amplifiers all mounted on a circuit board. The much more desired hybrid fiber-optic driver is yet to be delivered to NELC by an impending contract. It will be delivered at too late a date for consideration in the ALOFT Project.

a. Light Emitting Diodes (LEDs)

Light Emitting Diodes are the most widely used light source today. They will be used in the A-7 ALOFT Project because

of their availability and their operating characteristics which readily satisfy important characteristics which must be considered in the selection of a light source for fiber-optic systems. These characteristics are: [2]

(1) Wavelength of light output within frequency spectrum detectable by available photo detectors.

(2) Size of light source emitting region is compatible with the multi-fiber cables.

(3) The power requirement is compatible with the aircraft electrical system ($\leq$ 28vdc). Specifically, it is TTL compatible ($\angle$ 5vdc).

(4) Coupling efficiency allows light emission such that output power is radiated with an angle, θ, for efficient coupling to a fiber-optic cable. In addition, power efficiency of LEDs provides sufficient light to overcome coupling and cable loss and does not require external cooling.

(5) The response time of LEDs is fast enough so as not to distort high rate (15-20 Megabits) signals.

(6) LEDs, which have a much longer lifetime than laser diodes, are believed capable of operational lifetimes measured in hundreds to thousands of continuous hours at 25^{o}C.

A light emitting diode is a semiconductor chip which contains a P-N junction, mounted in a header and encapsulated beneath a transparent window. This semiconductor basically converts an electrical signal from the aircraft electrical system into an infrared ($\sim$ 9000 Å) light for transmission through a fiber-optic cable. Light emitting diodes make use of a P-N junction for light generation in much the same way as injection lasers except that no optical resonator is used to control the gain in the device.

The intensity of light output from the LEDs is proportional to the current through it. Thus, the amplifier output current controls the light intensity. Since LEDs operate at much lower current densities and optical densities than semiconductor lasers, they do not suffer unsolvable degradation and reliability problems.

The amount of information an LED can transmit is limited by its frequency response -- how fast it can be turned on and off. At this time LEDs can be modulated up to a few hundred megahertz. This is suitable for some 50,000 voice channels, which require 4000 Hz of bandwidth each, or some 30 TV channels, each requiring six MHz of bandwidth. [18]

Driver requirements for LEDs are much less severe than for semiconductor lasers. In general, the voltages on the LEDs and semiconductor lasers are approximately 2 to 3

volts. For some applications, LEDs with one TTL output, can be driven with currents of approximately 20 mA at frequencies not exceeding 30 MHz. For these device applications, transistor-transistor-logic (TTL) circuits are convenient drive circuits, whether they are off-the-shelf items or custom integrated circuits. [1] In summary, electronic drive circuits for LEDs and semiconductor lasers are readily available for requirements at least to 50 MHz.

b. Semiconductor Lasers

Of all the laser sources, the semiconductor laser holds the most promise for high data rate fiber-optic systems. Their characteristics of small size, simplicity of design, ease of high frequency modulation, and relative high power conversion efficiency make them ideal as light sources. [1]

A laser diode can be as small as a speck, barely visible to the eye. They are capable of emitting very narrow spectral outputs (spectral widths of less than a nanometer are possible), which makes them ideal for the microscopic core of a single mode fiber. Lasers can be pulsed in the gigahertz range, and thus can transmit far more information than an LED.

Several companies are now working on laser injection diodes. Corning Glass has developed fibers which have a square cross section which can be bonded side by side into a flat ribbon. This ribbon can then be bonded to a laser injection diode as shown in Figure III-14. [1]

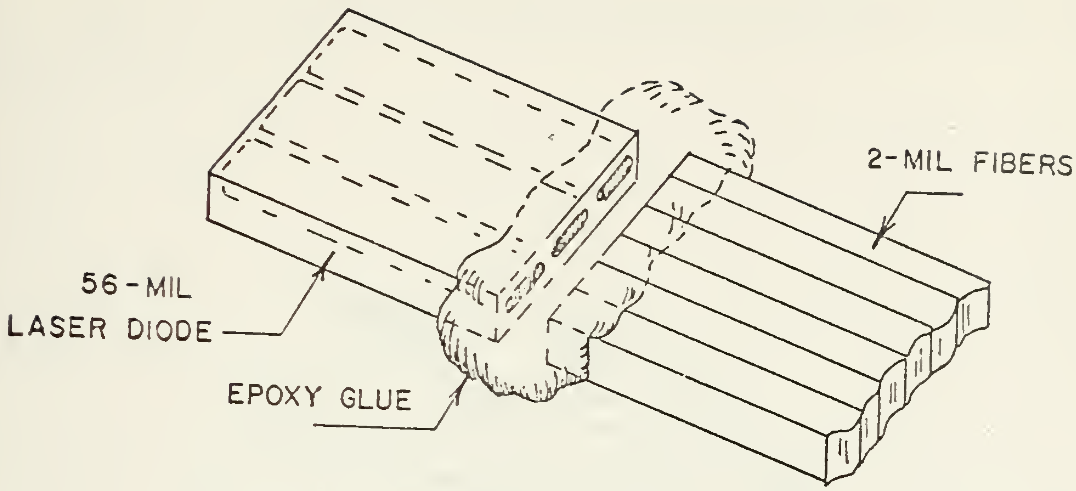


Figure III-14 Laser injection diode bonded to fibers

A few of the companies involved with laser injection diodes are: Sperry Rand, IBM, Bell Labs, and Texas Instruments. Bell Labs revealed in mid-1975 that they have been able to integrate familiar optical components such as lenses and prisms on special substrates. Bell has also integrated all the components needed to generate, modulate, deflect, and detect optical signals onto a single chip. [18] Most optical engineers feel that the greatest potential of laser diodes will be realized when integrated optical circuits (IOCs) are as common as integrated circuits (ICs) now used in calculators and other electronic equipment. Instead of transistors on a button size surface, IOCs will have microscopic lasers, modulators

(to put signals on a laser beam), photodetectors (to convert light back into electronic signals), and optical switches to route light into fibers for long distance communication. [18] Figure III-15.

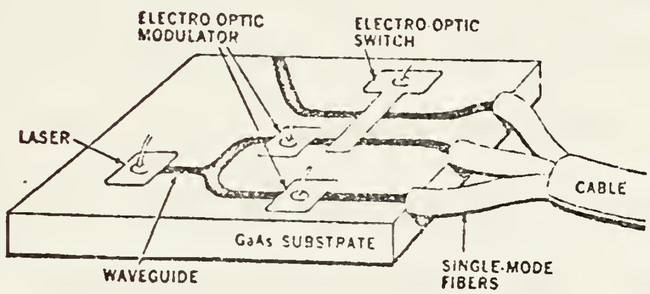


Figure III-15 Optical circuit on a chip as envisioned by Texas Instruments. Bell Labs recently formed such components on a single chip.

An important consideration of semiconductor lasers is that they can be modulated at extremely high rates. The modulation rate is intrinsically limited only by minority carrier lifetime in the semiconductor crystal. Carrier lifetime has been determined to be less that 10^{-10} seconds, which implies a modulation rate capability of ten gigahertz. [22] The bandwidth available is phenomenally higher. Light wavelengths involved translate into some 500,000 gigahertz -- enough bandwidth, theoretically to carry some 83 million TV signals simultaneously. The limitation in signal carrying capacity is how fast light sources can be modulated. [18]

5. Signal Receivers/Detectors

For the purpose of this study, detectors are analogous to a receiver. Optical signals are required to be demodulated through use of a photodetector which is sensitive to low light signal levels at the incident wavelength. A photodetector is a device in which the voltage or current output depends on the intensity of light falling on the light sensitive region of the device. The incident photons cause hole electron pair formation in the junction region which causes current to flow through the junction to an external load resistor which causes a voltage drop proportionate to the incident photons striking the detector junction. [28]

Detector requirements for fiber-optic applications are not particularly unique and much of the technology which has been developed in the past is applicable. However, some very important characteristics and requirements must be considered for fiber-optic applications: [2]

(1) Wavelength of transmitted light must be within the region of wavelength sensitivity of the receiver.

(2) The size of the light sensitive region of the receiver must be compatible with the particular fiber-optic cable for efficient light energy coupling.

(3) The electrical power system of the aircraft must be compatible with power required by the detector.

(4) Sensitivity must be such that incident light rays from the original signal source can be demodulated with a minimum amount of distortion.

(5) Mechanical constraints, such as simplicity, light weight, ruggedness, temperature coefficient, etc., must be met.

These conditions can be met by using commercially available positive intrinsic-negative (PIN) diodes with commercially available amplifiers. PIN diodes are quite satisfactory for short run applications such as the ALOFT system, but the avalanche photodiode is preferred in the long run where greater sensitivity is required in the bandwidth regime out to 15 megacycles per second. This improvement is obtained at the cost of more complex biasing networks and less proven reliability. [13]

D. SYSTEM DESCRIPTION OF FIBER OPTICS AS EMPLOYED IN THE A-7 ALOFT DEMONSTRATION

1. System Description

The original A-7 data communication system as utilized by the A-7 Navigation Weapons Delivery System (NWDS) is a point-to-point system which uses twisted pair wire and coaxial cable

interfaces in the Navy and Air Force versions of the operational aircraft. Certain portions of that system, as shown in Figure 1, Appendix A, are being converted to a multiplexed fiber-optic interface by the A-7 ALOFT Project. The original wiring will be left in the aircraft and will be reconnected for use upon completion of the A-7 ALOFT Demonstration. Since no change in the input/output (I/O) design of the avionics (other than the computer) was authorized, the fiber-optic interface with the peripheral avionics units has been achieved through external adapter units which contain all electro-optic and multiplexing/demultiplexing (MUX/DEMUX) circuitry and which are connected to the avionics with wire adapter cables.

The data communications encompassed by that portion of the system shown in Figure 1, Appendix A, which has been converted to a multiplexed fiber-optic interface by the ALOFT Project, consists of 123 signals. After electronic multiplexing, these signals are transmitted in the ALOFT Project over only 13 point-to-point fiber-optic cables, as opposed to approximately 300 wires which were required to transmit these same signals in the original A-7 system configuration. The fiber-optic configuration of the system is shown in Figure 2, Appendix A. Figure 3, Appendix A, shows only the electro-optic, MUX/DEMUX and fiber-optic portion of Figure 2, Appendix A, that is being

installed in the ALOFT Project. The computer shown in Figures 2 and 3, Appendix A, is an internally modified version of the original A-7 computer containing all necessary electronic multiplexing/demultiplexing circuitry to reduce the interface density required for the transmission of the signals to 13 channels of information flow at a maximum of a 10-megabit data rate. [14]

IV. AN APPROACH FOR A COST-EFFECTIVENESS STUDY OF AVIONICS DATA LINK ALTERNATIVES

A. GENERAL

Engineering research and development of fiber-optic cabling in aircraft has reached the stage where it is appropriate to begin assessing the cost and effectiveness of this emerging technology as a possible replacement for coaxial and twisted pair wire cabling in avionics data transmission wiring suites. The general approach for the analysis, as required by SECNAV INSTRUCTION 7000.14 A, and as desired by NAVAL ELECTRONICS LABORATORY CENTER, SAN DIEGO, is an economic analysis. An outline of this process is provided in Figure IV-1. The basic format of an economic analysis involves the determination of the cost and effectiveness of each of the competing alternatives, i.e., fiber optics and conventional wiring. Once this task is accomplished, the decision maker should be better able to make a rational choice between the competing systems.

The framework for cost and effectiveness analyses for any system usually follows one of two conceptual approaches:

(1) Fixed Effectiveness Approach - For a specified level of effectiveness to be attained in the

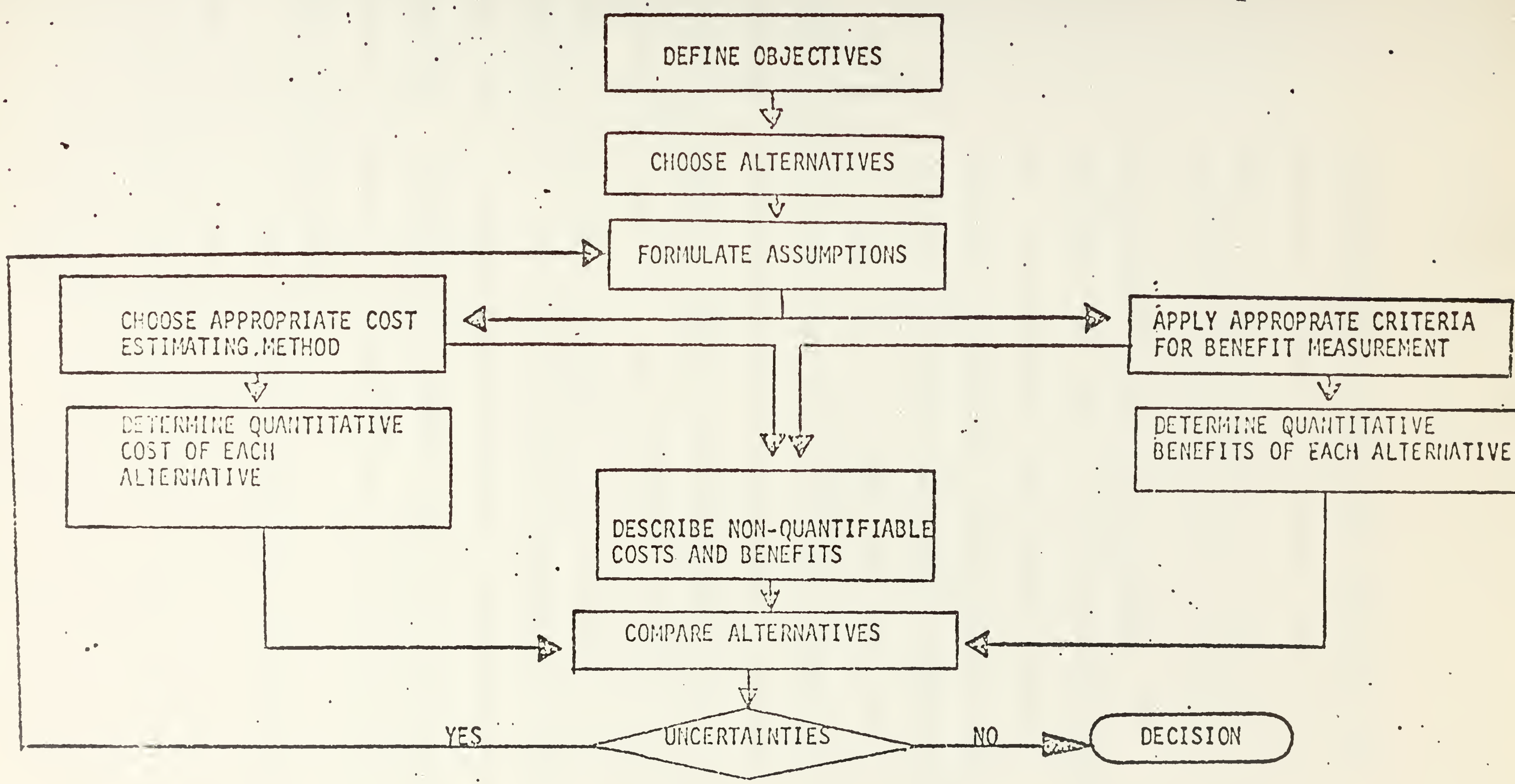


Figure IV-1 Economic analysis process

accomplishment of some given objective, the analysis attempts to determine that alternative which is likely to achieve the specified level of effectiveness at the lowest economic cost.

(2) Fixed Resource Expenditure Approach - For a specified cost level to be used in the attainment of some given objective, the analysis attempts to determine that alternative which is likely to produce the highest effectiveness. [17]

While either approach is possible, the fixed effectiveness approach might be more appropriate for the alternatives being considered in the case of data link systems. The fixed resource expenditure approach would apply more to an entire weapons system purchase, such as fighter aircraft, where a resource constraint can probably be more easily stated. Further, fixing resource levels would require extensive and detailed cost data at a subsystem level which is, in most cases, not available. Therefore, the authors feel it is appropriate to fix effectiveness at a desired level for both competing systems while minimizing costs.

A level of effectiveness as referred to in most cost-effectiveness publications usually relates to a single measure of effectiveness and the unit values that may be achieved for a given unit cost. In fiber optics there exists a myriad of

effectiveness measures that must be evaluated. A level of effectiveness for fiber optics would therefore consist of the quantification of all the MOEs.

Each specified level of effectiveness will have a cost associated with it resulting in the well known cost-effectiveness curve. Figures IV-2 and IV-3 serve as examples. Figure IV-2 illustrates the case where one alternative, B, exhibits "dominance" over its competitor, A, in every case. When dominance occurs, there is little need to proceed further with an analysis. Common sense would clearly indicate a choice of the dominant alternative. Figure IV-3 illustrates a case where alternative A exhibits dominance over alternative B over the range of the first four levels of effectiveness. However, alternative B is dominant at effectiveness level five and above. This could be of considerable significance if, for instance, weapons systems designers and decision makers insisted on acquiring a system capable of operating at effectiveness level five or above. Both alternatives could reach level five but at considerable cost differences. The obvious choice in this case is to choose alternative A for the first four levels of effectiveness and to choose alternative B if effectiveness level five is desired.

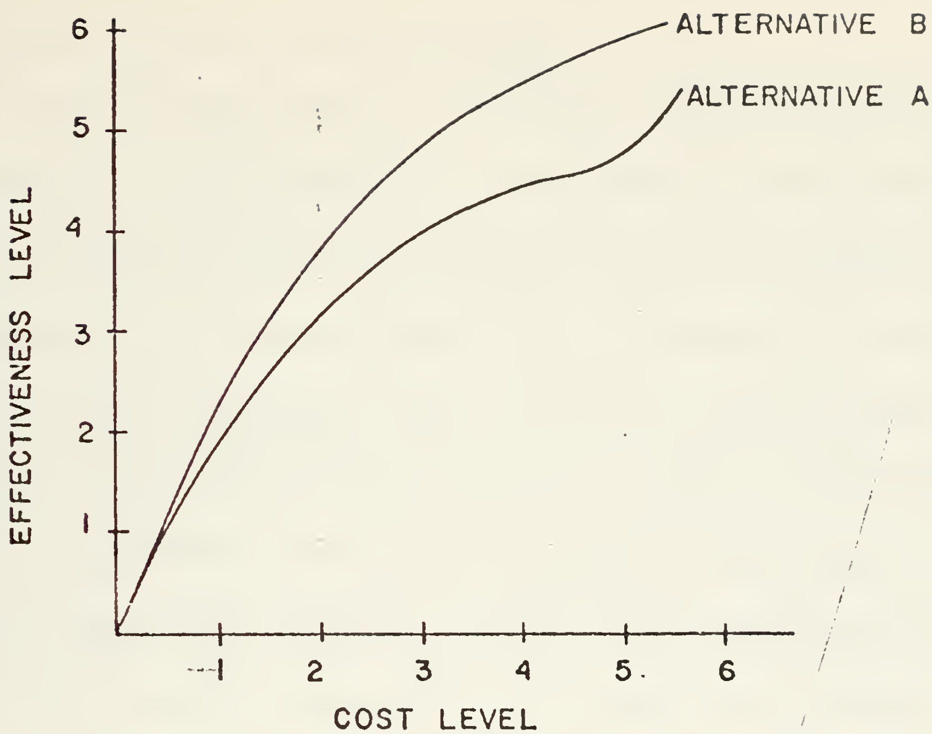


Figure IV-2 Hypothetical cost effectiveness curves displaying dominance

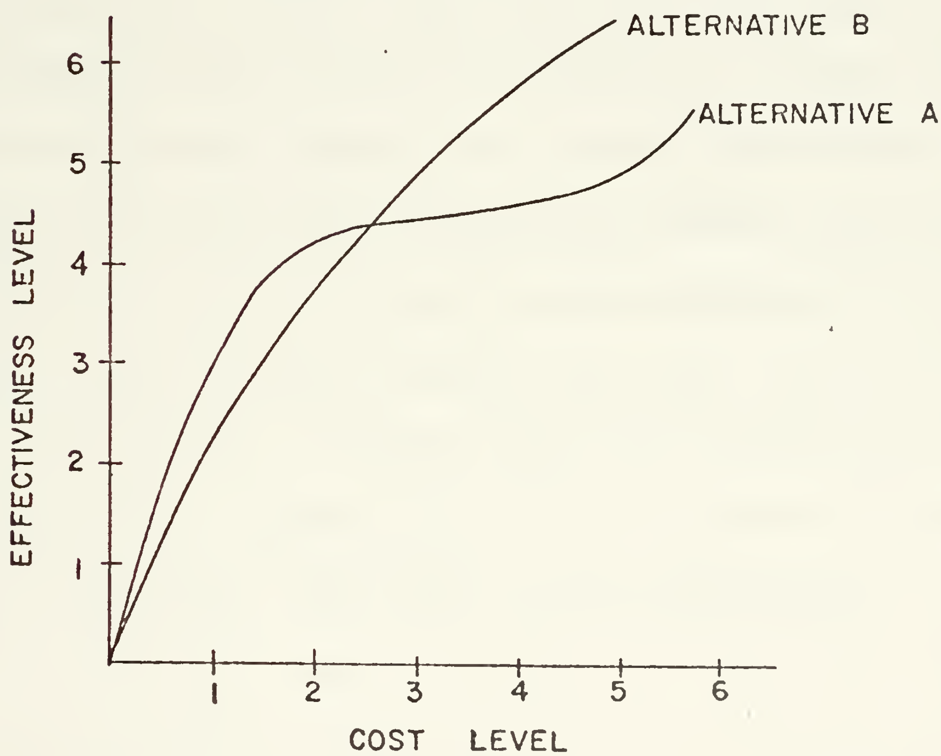


Figure IV-3 Hypothetical cost-effectiveness curves

B. MEASURES/LEVELS OF EFFECTIVENESS

The actual determination of measures of effectiveness (MOEs) will be accomplished by a contractor to be determined by NELC. Possible MOEs can be derived from the physical characteristics of the equipment such as weight and size as well as system performance characteristics such as data rate capacity and mean time between failure. Figure IV-4 lists several possible MOEs along with suggested measurement scales. If multiple MOEs are chosen to define effectiveness, a vector of MOEs will result. Collapsing the vector to a scalar introduces two problems. First, a method must be determined to combine MOEs measured by different scales. Typical scales to be considered are ordinal, linear interval, and ratio scales. Ratio scales, as used in such measurements as weight, volume, and mean time between failure, are special scales which have a natural zero point and an arbitrarily defined unit size. Linear interval scales, as used in measuring degrees centigrade, have an arbitrarily defined zero point and an artibrarily defined unit interval. Ordinal scales are measures of relativeness. Examples of ordinal scales include measures of hardness, measures of deterence, and degree of EMP/EMI immunity. In fact, many utility indices, such as rankings of cost and/or effectiveness issues by individual decision makers, are representable by ordinal scales. The second problem concerns the relative

weights that must be assigned to the components (MOEs) of the effectiveness vector. Such assignments are necessarily subjective because they depend totally on the judgment of the individual making the weighting assignments. Both problems, combining MOEs measured by different scales and assigning weights to the MOEs, can be eliminated if the fixed effectiveness approach is utilized since the competing systems will have the same effectiveness level.

When the relevant MOEs are determined, actual magnitudes can be assigned. The right hand side of Figure IV-4 illustrates five hypothetical assignments. The assignments represent five different levels of effectiveness that may be required or desired of the competing systems. Once the costs are determined for the competing systems at the different levels of effectiveness, the cost-effectiveness curves as illustrated in Figures IV-2 and IV-3 can be constructed. These curves then provide the decision maker with the necessary information to make a rational decision.

C. COST ANALYSIS

1. Life Cycle Costing

The costing methods as required by NELC will be done in terms of the life cycle costs (LCC) for both a coaxial and fiber-optic aircraft avionics system configuration as represented in the A-7 ALOFT Demonstration.

HYPOTHETICAL MEASURES OF EFFECTIVENESS (MOEs)	(MEASUREMENT UNIT)	(SCALE)	LEVELS OF EFFECTIVENESS (1 = Low, 5 = High)				
			1	2	3	4	5
Mean Time Between Failure	(Flight hrs)	R	1	5	10	20	20
Mean Time to Repair	(Maint. hrs)	R	5	5	3	2	1
Weight per avionics system	(Pounds)	R	125	125	100	50	25
Size, or volume, per avionics system	(Cubic feet)	R	20	20	10	5	3
Sparks, grounding, and fire hazard immunity	(Yes/No)	O	NO	NO	NO	NO	YES
Cable redundancy	(# of routes)	I	1	1	2	2	3+
EMP/EMI immunity	(Yes/No)	O	NO	NO	NO	NO	YES
Signal bandwidth	(Megahertz)	I	50	75	100	150	200
Signal attenuation	(dB/km)	R	300	300	200	100	20
Power consumption	(Watts)	I	50	50	20	10	5
Vibration tolerance (Mean Cycles to Failure)	(Cycles)	I	10,000	15,000	20,000	30,000	30,000
Heat resistance (Highest operating temp.)	(Degrees C)	I	50	60	70	80	80
Cold resistance (Lowest operating temp.)	(Degrees C)	I	0	-10	-20	-30	-30
Twist tolerance (Mean Twists to Failure)	(Twists per Foot)	R	3	4	5	7	7

Figure IV-4 Measures of effectiveness (hypothetical)

The task of estimating life cycle costs for wire interconnect components (coax/twisted pair, etc.) will be accomplished by a firm yet to be chosen by NELC. Currently, two NPS students, CDR R. Johnson and LT E. Knobloch, are developing a life cycle cost model which, together with the two suggested costing methods of this thesis, can be used by NELC to prepare cost estimates for the fiber-optic alternative.

Life cycle cost estimates used for making a particular decision, such as data link selection, need not be the total life cycle costs for the system. Costs which would be the same for each alternative and costs incurred prior to the decision (sunk costs) should be excluded. Sunk costs are those resources (money, etc.) which have been expended and which cannot be recovered. They are therefore irrelevant and should not influence future decisions. However, any assets created as a result of such expenditures are relevant.

Care must be used in the choice of costs to be excluded lest their omission improperly influence the decisions to be made. For example, consider one aspect of the present cost analysis. It has been decided to exclude the electronic equipment (including the MUX/DEMUX components) not incidental to drivers, connectors, cables, and receivers because those equipment costs appear to be common to both data link alternatives. This restricts the analysis to the trade-off between the costs

and reliability of competing alternatives. One might consider whether or not the costs of the MUX/DEMUX units are really common to both alternatives. For instance, electronics manufacturers might find it more costly to modify their standard electronic units to accomodate fiber-optic components (such as multi-channel bulkhead connectors, etc.) than to use off-the-shelf units for conventional wiring/cabling. Thus the assumption on which the MUX/DEMUX equipment costs were excluded would prove to be invalid.

NELC has undertaken the preliminary definition of relevant LCC elements for the purposes of defining a LCC model. The cost elements listed in Figure IV-5 were derived by NELC after examining over 600 documents on life cycle costing, or subjects related thereto. The search included local, navy-wide, DoD, and private industrial firms that have apparent expertise in electronics and communications equipment and systems life cycle costs. [29]

2. Cost Data Collection Effort

Cost data collection, one of the first steps of a cost analysis, provides specific costs for elements of the system on which a simple price tag can be placed, or for which a nominal extension can be made of costs experienced in similar programs. A literature search and telephone survey by the authors confirm the generally known fact that cost data for

1.0 RDT&E Costs are assumed as sunk costs for this study only.

2.0 Investment Costs

- 2.1 Prime Mission Equipment (PME)
- 2.2 Installation
- 2.3 Support and Test Equipment
- 2.4 Initial Supplies
- 2.5 Initial Training
- 2.6 Inventory Management/Support
- 2.7 Initial Transportation

3.0 Operations and Support Costs

- 3.1 Operations
  - 3.1.1 Operations Personnel
  - 3.1.2 Training
- 3.2 Support
  - 3.2.1 Maintenance Labor
  - 3.2.2 Replenishment Spares and Material
  - 3.2.3 Transportation
  - 3.2.4 Maintenance Training
  - 3.2.5 Support Equipment Maintenance

Figure IV-5 Life cycle cost elements

elements of a fiber-optic data link system, other than pre-production prototype costs, are not generally available. It is true that costs (i.e., price to the user) of fiber-optic systems components such as cables, connectors, receivers and drivers, can be obtained -- but these prices usually reflect contract prices on one-time bids. The prices paid today are not indicative of prices that will be paid tomorrow for components produced on either a one-time contract basis or a full production mode basis.

Most of the available cost information has been obtained from NELC sources (APPENDICES C, D, and E). The cost information provided by NELC has been verified by the authors as being representative of the wide range of costs generally associated with components of an emerging technology.

One of the principle reasons for wide cost dispersions is the lack of standardization of component parts. For instance, if one needed a fiber-optic system to perform a particular function, and if this person was to approach several fiber-optic manufacturers for bids, he would immediately be faced with the problem of non-comparability of different manufacturers' components. The customer would be faced with the problem of defining perhaps dozens of his own desired design requirements: single mode, multimode (how many fibers?), desired cabling (will it be toxic upon decomposition?), packing fraction, numerical aperture,

index of refraction, attenuation limits, flexibility, diameter, per cent breakage tolerance, etc. After defining his needs, he should not be surprised to learn that no two manufacturers have similar cables to meet his needs, nor are standardized couplers, drivers and receivers available. The customer would find, however, that a fiber-optic system could be designed and built to meet his needs -- but at considerably higher cost than he might have first anticipated.

A few examples will be given to illustrate the uncertainties involved in gathering data for component costs.

Although module driver/receiver units have cost in the range of hundreds of dollars, Mr. J. R. Biard, of Spectronics, Inc., indicates that it would not be unreasonable to expect to see prices for driver/receiver modules drop to a \$10 - \$12 range when in full production. [7]

Galileo's 400 dB/km multimode cable was selling for \$2.50/ft in 1974. It was selling for \$0.75/ft in August 1975. Mr. Rodney Anderson, of Galileo, indicates that he could reduce that price by half, or more, with purchase quantities greater than 100,000 feet. He feels that his 35 mil fiber-optic bundle could compete with micro-coax cable on a cost-per-foot basis but, as yet, there is not enough consumer demand to generate cost savings which in turn, with competition, would lead to the lowering of prices below \$0.75/ft. [4]

Mr. Robert Freiberger, of Corning Glass Works, states that his company "has been in a full production mode for fiber-optic bundles for the past 7-8 years." [19] In 1974, Corning's 19-mode 30 dB/km cable was selling for $17.37/ft when sold in less than 5,000 meter quantities. Corning reduced attenuation from 30 dB/km to 20 dB/km at the 820 nm wavelength while reducing the price by 36 percent in 1975. The price in mid-1975 was $10.97/ft for purchase orders of less than 5,000 meters and $5.56/ft for purchases greater than 5,000 meters. Corning's current emphasis, however, is on single-mode cables rather than multimode bundles. Corning's most important fiber-optic product is a single-mode low-loss ($<$ 6dB/km) cable called CORGUIDE. CORGUIDE presently sells for $13.50 per meter or about $4.11 per foot. This equates to about $.59 per foot for each low-loss fiber as there are seven individual fibers in CORGUIDE.

"Corning is putting millions of dollars yearly into fiber optics research and development," states Mr. Freiberger. One of their recent developments, in conjunction with the Deutsch Co., has been the development of a hopefully reliable mechanical fiber-to-fiber connector for single-mode cables. Corning's efforts are aimed directly at capturing a major portion of the potentially large market that will result from fiber optics utilization by American Telephone and Telegraph Co. in the 1980's. Mr. Freiberger sees little chance of lowering prices

for a military market in fiber optics in the near future as it would take a potential $100 million per year market to induce Corning to drastically lower prices or alter production. "In a full production mode, with markets above $100 million per year," Mr. Freiberger states, "it would not be unreasonable to look for costs of CORGUIDE to drop from $4.11 per foot to about $.10 per foot. This equates to a little over 1¢ per foot for low-loss fiber." Mr. Freiberger makes the interesting prediction that Corning's costs of production for low-loss fibers will continue to decrease. As this occurs, the currently less expensive medium-loss multimode fiber-optic bundle (with hundreds of individual fibers in each bundle) will become more costly to produce than low-loss cables such as CORGUIDE. [19]

Costs for connectors are not, in general, as uncertain as other fiber-optic component costs. The exception would be the 13-channel bulkhead connector developed by ITT Cannon Co. for NELC/IBM at a price of $500 each for a total of six connectors. [31] It has subsequently been reported to the authors that ITT Cannon Co. has sold this same connector to a leading aircraft manufacturing company at a price of $50.00 each. [14]

Single channel connector costs are nominally low at $2.50 - $3.50 each. This lower price is generally attributed to the fact that mechanical connector technology and manufacture is not new. Connector manufacturing companies already have the

production base necessary to produce fiber-optic connectors for multimode cables.

The authors were unable to obtain any meaningful estimates of the costs of fiber-optic integrated optical circuits (IOCs). According to Mr. Biard of Spectronics, Inc., the development of integrated optical circuits today is in the same relative position that integrated circuits were in in 1958 -- a full three to four years before a firm production base was established. [7] Mr. Biard makes one clear distinction, however; in 1958, the electronics industry was receiving substantial financial assistance from the U.S. Air Force for the specific purpose of perfecting and developing integrated circuits. The electronics industry today is not receiving the funds and support necessary for the same pace of development. Mr. Biard feels that unless more government funds are made available for the purpose of IOC research and development, integrated optical circuit growth and development will be much slower than the previous growth of integrated circuits. Ample statistical data exist in the field of integrated circuits such that meaningful cost analogies, for the purpose of predicting costs, could be utilized once a cost data base has been established for IOCs.

It is the authors' assessment that a more detailed cost gathering effort was not warranted at the time of this writing.

Statistical data could not be correlated because, in many cases, there was no common ground for comparison. It was generally observed, however, that costs are definitely in a downward trend. The rate of price decline will continue to depend on demand and technological development trends but it would not be unreasonable to expect prototype costs of some components to be reduced by a factor of 10 within the next few years.

D. COMBINING COST AND EFFECTIVENESS

1. Ordering Uncertainties Through Scenarios

Technological forecasting is by definition, an area fraught with uncertainty. It has been seen in earlier discussions in this work that technological developments in the field of fiber optics have many uncertainties -- all of which should be considered by a decision maker. For example, before a decision maker can make a final choice of future avionics data link systems, he must face the overall questions of how, when and why to implement any given system. In the case of fiber optics, he must concern himself with the future technical composition of the fiber-optic data link. One most certainly would not choose the one-time application of discrete circuitry used in the A-7 ALOFT Demonstration. In fact, technological developments are accruing so rapidly, he might not choose any

of the now existing components. Listed below are several of the important uncertainties about which a decision maker must be concerned:

(1) Technological levels of sophistication desired for fiber optics: multimode or single mode fiber-optic cables; low-, medium-, or high-loss cables; point-to-point or data bus systems; data capability rates of kilo-, mega-, or giga-bits per second; discrete, modular, or integrated optical circuits; rugged strength or small size, light weight cables; redundant or single path data links; LED drivers or laser injection diode drivers; standardization of components to meet military specifications; low-loss T- and Star couplers; reliable single mode mechanical connectors; bandwidth -- How much is "enough," etc.?

(2) Avionics systems design requirements: Will military decision makers insist on higher EMP/EMI immunity standards for future avionics systems; Will data transfer rate requirements for complex computerized avionics systems be increased beyond present data link capacity; Will wiring-path redundacy be required for increased reliability/survivability; Should avionics systems be utilized in any one type of

military aircraft -- or all types of military aircraft; Are fiber-optic data links desirable for all weapons systems; etc.?

(3) Timing: When will each of the technological developments mentioned in (1) above be off-the-shelf available; When will technological advances level-off enough to preclude an existing generation of fiber-optic components from approaching either apparent or perceived obsolescence as happened in the case of 1st, 2nd, and 3rd generation computers; When will there be sufficient market potential to induce fiber-optic producers to mass produce components; Does even the strongest possibility of a military "go-ahead" in this area offer enough incentive for industry to establish a production base for mass production; What market potential (measured in millions of dollars and/or millions of feet of cable) will be sufficient inducement to industry; When will military design requirements force military decision makers to utilize fiber optics in order to meet EMP/EMI immunity requirements; When (and how much) will government sponsored R&D funds be made available to industry and/or the military for continuing research and development; When will data transfer rates greater than the limits

of coax cable be required; When will the fiber-optic data link system be technically and/or economically feasible for avionics suites; What is the earliest time frame we could expect to use fiber optics in shipboard use; etc.?

The uncertainties described above can present a confusing situation when taken together. Scenario construction often offers relief in this area by structuring uncertainties in a logical sequence of events in order to show how, starting from the present, or a base year such as the beginning of FY 1977, a future state might evolve, step by step, to a terminal date, say 1990. The purpose is <u>not</u> to predict the future, but to refine information on the forseeable "climate" for various fiber-optic technological advances and system utilizations. Kahn, in the introductory chapter to his study on scenario technique, emphasizes that "the scenario is particularly suited to dealing with several aspects of a problem more or less simultaneously." [24]

Through the use of a relatively extensive scenario, the analyst may be able to get a "feel" for events and for the branching points dependent upon critical choices. These branches can then be explored systematically. The authors have attempted to structure several events and branches on a representative

basis of (1) a neutral context, (2) a modestly optimistic context, and (3) a modestly pessimistic context. It should be emphasized that these are only three of an infinite number of possible scenarios. An entire study could be made on the dozens of uncertainty branch points and the resultant event trees which could develop from each.

Two of the advantages that Kahn points out in his discussions are: Scenarios are one of the most effective tools in lessening "carry-over" thinking; scenarios force one "to plunge into the unfamiliar and rapidly changing world of the present and of the future by dramatising and illustrating the possibilities they focus on." Secondly, scenarios "force the analyst to deal with details and dynamics which he might easily avoid treating if he restricted himself to abstract considerations. Typically, no particular set of the many possible sets of details and dynamics seems specially worth treating, so none are treated, even though a detailed investigation of even a few arbitrarily chosen cases can be most helpful." [24]

The analyst should be aware that certain dangers may arise from the use of scenarios to help guide and facilitate further thinking and analysis. Specifically, the initial conjectures might be assumed erroneously to be sufficiently correct to lead to scenarios with some content of "reality." However, as Kahn remarks, "a specific estimate, conjecture, or

context, even if it is later shown to have serious defects, is often better than a deliberate blank which tends to stop thought and research."

a. Scenario I - A Neutral Context

The scenario begins in October, 1976, the beginning of the 1977 Fiscal Year -- the year that NELC has chosen for an economic analysis for fiber optics. One million feet of fiber-optic cable is produced annually. Flight testing of the A-7 fiber optics demonstration aircraft has been completed as scheduled. The results of the first Delphi questionnaire have been received and refined. These results, together with the life cycle cost model constructed by NPS and NELC, have been exercised. The results are such that it has been decided to expand the model to analyze a particular multiplexed data bus system utilizing the building block components described in NELC TD-435. (See Appendix C) By October 1977, with the expansion of the models, a trade-off analysis is performed for a data bus concept. The results of the economic analysis indicate a choice of parity between fiber optics and coaxial systems. There seems to be no question of the technical feasibility. Test results indicate that desired EMI/EMP immunity can be obtained. It is decided by military aircraft designers and decision makers to utilize multimode fiber optics with modular LED circuits on a limited number of aircraft as a pilot

application. A multiplexed multimode data bus avionics system will be designed and installed in the Navy's 16 ES3 aircraft being developed for the Tactical Airborne Surveillance Exploitation System (TASES) program. The aircraft will be built in 1981. It is decided that this will be the only multimode application. Future aircraft avionics designs will utilize single mode if the TASES avionics systems work well. These follow-on military aircraft of the mid-to-late 1980's will also utilize IOCs. By mid-1977, fiber optics are still primarily used in laboratory and test demonstrations. Demand is small. Any one of the major fiber-optic cable producers is able to produce enough high-, medium-, or low-loss fiber-optic cable in a period of only a few weeks to satisfy the market demand of the entire United States for one year. Fiber-optic cable production in 1978 totals two million feet. As of 1978, there is no standardization of components (cable size, connectors, circuits, etc). Modular type driver and receiver circuits have been produced in small quantities on contract bases for various contractors to use in laboratory applications of multimode and single mode fiber optics for the past two years. Successful demonstrations of T- and Star-couplers have encouraged the Navy to conduct further demonstrations of fiber optics feasibility. Following the "float-off" sea trials between the Rohr and Bell Cos., the prototype 2000-ton Surface Effects Ship (2KSES) is

to receive a fiber optics data bus system, utilizing multimode cables, in 1978. The data bus system utilizes prototype T-couplers and modular driver and receiver circuits. In 1978 it is decided to use fiber optics in the avionics package of the VPX (replacement aircraft for the Navy's P-3). The Navy, now convinced of the technical feasibility of fiber optics, plans to use a single mode fiber-optic data bus system in the VPX when production commences in 1983. It is apparent during the 1978-1979 time period that the military is the primary user of multimode fiber-optic cable. Cables, connectors, modular drivers, etc., have been standardized for military application, but much of this effort will be of questionable value as multimode applications are planned to be phased out, during a five-year period, in favor of single mode applications. Industry's efforts are concentrated on technological developments relating to single mode cables in conjunction with integrated optical circuits. The sale of multimode cables to military consumers has little financial impact on the producers. They are not dependent on a military market. The Navy and Air Force have decided against large scale retrofit programs. However, the Air Force is retrofitting one B-1 bomber in a program similar to the ALOFT Demonstration. The Air Force will utilize a single mode data bus system in the B-1 Demonstration. They will use prototype components developed by industry. By 1980, the U.S.

Army has begun to replace an initial segment of four million feet of tactical communication lines with single mode fiber-optic cable. Their plans are to replace a total of 16 million feet of 26 pair coax cable by 1985. One fiber optics producer wins the contract, but he is still not dependent on the Army for continuing profits, etc. Because fiber-optic cable is relatively simple to make, he is able to stay far ahead of the Army's need through use of his pilot plant facility, and in fact can produce the entire 16 million feet of cable with only a few months of productive effort. Industry is still concentrating on the single mode market. Production in 1980 totals three million feet of fiber-optic cable. In 1980, the United States is experiencing a rate of inflation of 6-7 percent per year, but certain materials are considered "strategic" and are in short supply. Copper is one of these strategic materials. The price of copper (in terms of constant 1975 dollars) has more than doubled, while the cost of raw materials for glass (also in terms of 1975 constant dollars) has remained constant. There are sufficient raw material reserves for glass in the U.S. to last for an estimated 100 years. The cost of petroleum base products has risen in a manner similar to that of copper and thus has caused the costs of fiber optics protective cabling to double. Almost all laboratory and test bed demonstrations utilize single mode cables in conjunction with IOCs by 1981.

By 1983, low-loss (< 5 dB/km) long distance fiber-optic cables are a reality. The Corning Glass Co. is in a full production mode for the production of single mode fiber-optic cable. American Telephone & Telegraph Co., the principle receiver of Corning's output, begins replacement of one million feet of aging coax and twisted pair cabling. Six million feet of fiber-optic cable is produced in 1983. One million feet of cable will be replaced during each of the first two years. This replacement rate will be increased to five million feet per year in 1985. During the period of the mid-1980's, fiber-optic applications boom, but the largest users are companies in the communication industry. In retrospect, it can be seen that technology development rates during the late 1970's and early 1980's were quite significant. However, production growth rates were almost stagnant by comparison. Industrial producers utilized their pilot operations to produce only enough to satisfy occasional customers such as the military, and experimental laboratories. In the early 1980's, the military began to design avionics systems for single mode data bus applications. Twelve million feet of fiber-optic cable are produced in 1986. By 1987 there is increasing fiber optics applications by computer companies, electric power companies, aerospace industries, civil aviation firms, etc. This continuous demand helps maintain a stable production growth rate of 50 percent

per year. In 1988, 23 million feet of fiber-optic cable are produced. Component prices start a continuous decline over a period of time in accordance with the experience curve theory as explained in this thesis. Total industry output is 46 million feet of cable per year in 1990.

b. Scenario II - A Modestly Optimistic Context

During FY 1977, interest in fiber-optic systems has increased to the point that other follow-on fiber optics demonstrations are planned. The successful A-7 ALOFT Demonstration has proven the technical feasibility of point-to-point multimode applications. The cost models developed by NPS and NELC are utilized by analysts who conclude that single mode applications will be used in yet to be determined future military aircraft. The resounding success of the A-7 ALOFT Demonstration has helped pave the way for a similar demonstration with the Air Force's F-15. Funds have been made available for the Air Force Avionics Laboratory to replace the conventional coax data bus system of an operational F-15 with a fiber-optic data bus system. Prototype T-couplers and modular hybrid cricuits are used with multimode fiber-optic cables. One million feet of fiber-optic cable is produced in 1977. In early 1978, infrared light emitting diodes are beginning to be replaced with laser injection diodes for laboratory applications. Monolithic integrated LED circuits are introduced as standardized fiber-optic

components in 1978. In early 1979, the prototype 2000-ton Surface Effects Ship (2KSES) demonstrates the feasibility of a fiber-optic data bus system using multimode fiber-optic cables. It is decided that future data bus applications will utilize a single mode fiber-optic cable in conjunction with IOCs. Multimode cables will not be used in operational aircraft avionics systems. The decision is made in 1979 to utilize a single mode data bus system in the VPX (replacement for the P-3). The aircraft is to be built in the mid-1980's. In 1979, monolithic integrated optical circuits have been perfected and are available commercially. However, they won't be mass produced until the American Telephone and Telegraph Co. begins use of fiber optics in 1983. Even though interest is high, demand for fiber-optic components does not warrant full scale industrial production. The fiber-optic cable producers can keep up with demand with only a few production hours each day. Total production is four million feet of cable per year in 1980. By 1980, standardization of components has been completed. Single mode cable connectors have been successfully demonstrated for three years. By 1981, integrated optical circuits are off-the-shelf items but supply is limited because they are not full production items. However, their continuing successful use in laboratory applications indicate that the real future of fiber optics continues to point to integrated optical circuits

together with single mode cable as the desired goal of fiber optics technology. The successful Air Force F-15 Demonstration in 1981 has further convinced the Navy and Air Force to plan future avionics systems around the single mode data bus concept. The B-1 bomber demonstration in 1982 was a success. The application of fiber optics helped reduce total weight by six hundred pounds yet provided ample EMP/EMI protection. The Army starts replacing five million feet of tactical communication line in 1982. Army plans call for a replacement of 16 million feet of 26 pair coax cable by 1985. This will be followed by the replacement of 25-50 million feet of permanent long distance communication lines by 1990. In 1982, demand for low-loss single mode cable by the Army accounts for almost 50 percent of the total U.S. demand (4 million feet per year). The Army's share of the user market will dwindle to only a few percent per year after AT&T starts its replacement program. By 1983, AT&T is using ten million feet of single mode cable each year. 1983 is considered the base production year with a total production of 8 million feet per year. Russia, Japan and European countries are also active in the fiber optics market. Empirical data can now be gathered to verify growth rates of approximately 50 percent per year. In 1984, the VPX aircraft is built. It utilizes single mode fiber optics. In 1985, AT&T has the only data link system capable of handling

the high data rates required for a data bused "wired city" concept. A few strategically placed buses in a city are capable of transmitting data at the gigabit level. Other telecommunication companies prepare to follow AT&T's lead. By 1986 they are installing their own fiber-optic lines. After the additional telecommunications companies enter the market, production growth rates steady at 50 percent per year as total production is now 20 million feet of fiber-optic cable per year in 1986. Total production is 45 million feet of cable per year in 1988, 100 million feet per year in 1990. Newly constructed military aircraft avionics systems all use the fiber-optic data bus concept by 1989. New ships also use fiber-optic data bus. Total military usage is approximately five million feet per year, or only a fraction of the total used by the major communications companies.

c. Scenario III - a Modestly Pessimistic Context

Flight testing of the A-7 ALOFT Demonstration aircraft has neither proved nor disproved any of the claims of hopeful proponents of fiber-optic systems. Results from the Delphi questionnaire were somewhat late in being received. This, coupled with a less than satisfactory data collection for the life cycle cost model, has delayed the proposed economic analysis for a period of several months. The decision points on whether or not to use fiber optics in the avionics

packages of the proposed LAMPS helicopter, VPX (P-3 replacement), TASES (ES3's), and VPX (F-14 fighter follow-on), pass without a conclusive economic analysis from the ALOFT Demonstration. The decision is made to continue to use known reliable coaxial systems in the above mentioned aircraft. One reason given by military planners is that the SALT II Agreements with the Russians, among other things, were so successful that the needs of EMP/EMI immunity are no longer a driving force. It has also been argued very successfully by newly formed coaxial cable manufacturers' lobby groups in Washington that the coax/twisted pair data bus system of the F-15 has functioned perfectly well for years. "Besides," they argue, "think of the thousands of productive workers who will be thrown out of work if coax is no longer used." Military planners decide to use protective shielding for EMP/EMI immunity if and when the need arises. In 1978, because of constant pressure from Congress to "cut the fat" out of the military budget, R&D funds for fiber optics research are "cut to the bone." The planned 2KSES shipboard application is cancelled. It is clear that the 1980-1987 generation of military aircraft avionics systems will not utilize fiber optics. In the period 1978-1985, NELC, the Air Force Avionics Laboratory, and the Army Electronics Command use their limited R&D funds to their best advantage in continuing to demonstrate

the technical feasibility of fiber optics applications as data transfer links. All technological developments, such as laser injection integrated optical circuits, single mode connectors, T-couplers, and Star-couplers are slowly standardized -- mainly as a result of the military's Tri-Service effort in this area. A firm production base is not yet established but, as components become standardized, and as more component firms enter the market, prices to consumers continue to drop. Between 1980 and 1982, production doubles to two million feet of cable (mostly single mode) as more potential users are beginning to follow the lead of American Telephone and Telegraph Co. In 1983, with production at four million feet of cable per year, AT&T begins to replace its first million feet of aged long distance communication line. 1983 is considered to be the base year for production. More telecommunication companies follow AT&T's lead in the late 1980's, mostly because the strategic aspect of copper availability has driven them to find a substitute cable. Copper prices have more than tripled since 1975 (constant 1975 dollars). Raw materials for fiberglass, on the other hand, are not strategic in nature and are available at about the same relative cost. The strategic nature of petroleum based products has tripled the cost of fiber-optic protective cabling. Production totals eight million feet of fiber-optic cable in 1986. The

mid- to late-1980's see constant growth rates of 30 percent per year. Total production is put at 22 million feet per year in 1990. This period in the late 1980's sees the military designing operational single mode data bus avionics systems for aircraft to be built in the early 1990's. The Army begins to replace the first segment (one million feet) of tactical communication line in 1987. The Army will replace all 16 million feet of its coax line by 1995.

The three scenarios presented are the authors' own perceptions of how the fiber-optic industry might develop. Some of the information contained in the scenarios, however, was obtained from a literature review and conversations with military and industry contacts. The scenarios provide a framework for hypothesizing how the fiber-optic industry might evolve over time. It should be emphasized that many more scenarios could be developed by varying relevant branch points or events such as technological advances and military and civilian demand requirements. To summarize some of the information provided in the three scenarios, the following graph (Figure IV-6) represents the annual production demand quantities for Scenarios I, II and III for fiber-optic cabling by production year.

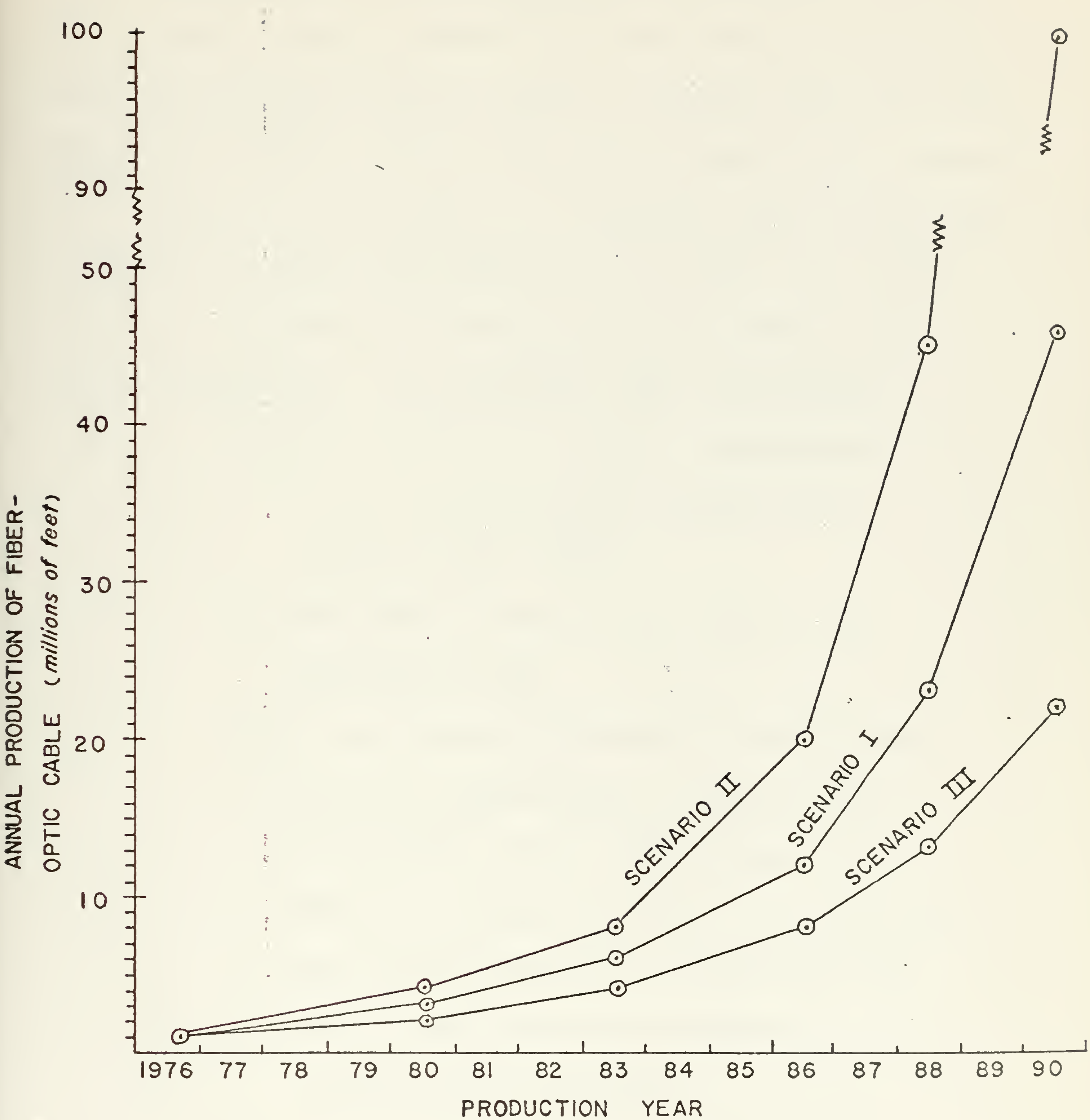


Figure IV-6 Fiber-optic cable demand, by scenarios

2. Constructing Cost-Effectiveness Curves from Scenarios

In addition to ordering and structuring uncertainties existing in the fiber-optic industry, scenarios implicitly provide the information for cost and effectiveness levels required for the comparative analysis. To illustrate how scenarios can be used to construct cost-effectiveness curves, it is appropriate to summarize the characteristics of scenarios and related assumptions. The following items are relevant:

(1) Each scenario is a list of assumptions of how the fiber optics industry and technology may evolve.

(2) The events listed in the scenarios are explicit in time.

(3) At any time in the scenarios the specified levels of effectiveness, in most cases, are possible. If an effectiveness level cannot be achieved, then the cost-effectiveness analysis cannot be accomplished and infinite cost should be assigned to eliminate the alternative.

(4) The cost of achieving a specified level of effectiveness are scenario and time dependent.

With these characteristics and assumptions it is possible to construct the matrices shown in Figure IV-7.

SCENARIO A

EFFECTIVENESS LEVEL / YEAR	E_1	E_2	E_3	E_4	E_5
1976					
1977					
1978			C_{83}		
1979					
1980					

SCENARIO B

EFFECTIVENESS LEVEL / YEAR	E_1	E_2	E_3	E_4	E_5
1976					
1977					
1978			C_{83}		
1979					
1980					

Figure IV-7 Scenario/effectiveness/time matrices

The elements of the matrices are the cost, C_{ij}, where i specifies the year and j the effectiveness level required. The rows of either matrix trace out the cost-effectiveness

curve for a particular year at five effectiveness levels. Possible cost-effectiveness curves for 1978 are constructed for scenario A and B in Figure IV-8.

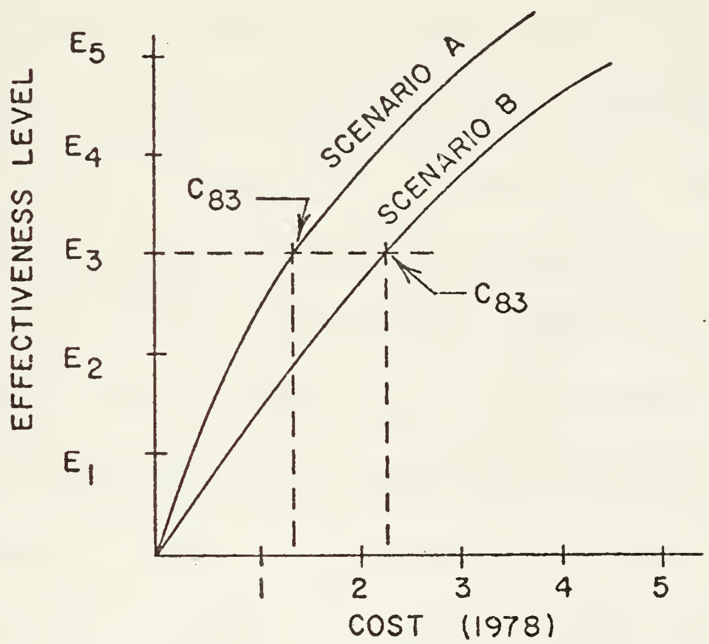


Figure IV-8 Scenario related cost-effectiveness curves

To illustrate how scenarios can be used to construct cost-effectiveness curves for the fiber-optic alternative, scenarios A and B are first defined. Assume scenario A depicts rapid technological advances, standardization of components, and high demand from the civilian community while scenario B represents continued research and development outlays, no civilian demand, and prototype components. If effectiveness level three is desired in 1978, then the C_{83} cost element should be computed for scenarios A and B utilizing the life

cycle cost model (Figure IV-5) together with the assumptions of the respective scenarios. Since the scenarios contain demand quantities and growth rates for fiber-optic components, cost estimates can be made for these components by utilizing the experience curve or other applicable techniques. Experience curves will be discussed in Section V-C. The component cost estimates then can be applied to the life cycle cost model to obtain the C_{83} cost element. Estimating costs for the five effectiveness levels and both scenarios results in the cost-effectiveness curves depicted in Figure IV-7.

Scenarios, therefore, provide the basis from which cost estimates can be made. The selection of a particular scenario, from the many possible scenarios, should be assessed in terms of the likelihood of occurrence of particular scenarios. As a possible method of minimizing or limiting the number of scenarios and refining estimates contained in scenarios, the authors suggest using the Delphi technique to be discussed in Section V-B.

V. TWO COSTING TECHNIQUES FOR FIBER OPTICS

A. GENERAL

In this section, two techniques for costing fiber optics are discussed. First, the Delphi technique is discussed as a method of obtaining estimates identified in and required for scenarios. These estimates include such items as demand quantities, growth rates, and technological advances. The second technique, the experience curve, is then explained. It permits the estimation of costs to the government based on cumulative quantity produced. This discussion is followed by a demonstration showing how the estimates contained in the scenarios can be applied to the experience curve to predict the future price behavior of fiber-optic components.

B. THE DELPHI TECHNIQUE

In fiber optics, data do not exist to establish firm technological, price or demand trends. In this case, regression, sampling, smoothing or other mathematical analyses are not applicable as a basis for forecasts. Hence, predictions must rely on the opinions of experts. Kahn makes the observation that many books go into considerable detail on the methodology of forecasting, particularly technological forecasting. While the methods seem very impressive when

viewed in terms of how successful they are, their track record is not as good as some of their proponents would suggest. [24] Kahn, however, expresses great interest in the Delphi method which he thinks has great potential in areas involving emerging technologies.

Kahn makes the statement that while Delphi is an excellent method of technological forecasting, it works best when it polls the experts who are actually attempting to achieve the given result. Not only will they have some idea when the innovation can be expected, but they could also have a large influence on program outcomes.

Delphi, as a technological forecasting technique, is generally credited to Olaf Helmer, T. J. Gordon, and N. C. Dalkey of the RAND Corporation. Initial work was done by Helmer as early as 1959. Helmer's publication of a "Report on a Long-Range Forecasting Study" by the RAND Corporation, in 1964, discussed the Delphi technique in detail. [20] In his report, he describes his now well known method of soliciting forecasts from a panel of experts in order to deal with specific questions, such as when will a new process gain widespread acceptance or what new developments will take place in a given field of study. Instead of the participants gathering together to discuss or debate the questions, they

are kept apart, usually answering assigned questionnaires through written or other formal means, such as on-line computers.

The advantages of using Delphi to poll the experts then are: (1) The Delphi seeks to systematically codify the opinions of experts while minimizing bias. (2) It polls the experts who are actually attempting to achieve the given results. (3) It eliminates typical problems of face-to-face interactions among members of a panel. Many of these problems are psychological factors which tend to reduce the value of methods based on face-to-face interaction (e.g., brainstorming sessions). [23] Some of these psychological factors are: unwillingness to back down from publicly announced positions, personal antipathy to or excess respect for the opinions of a particular individual, skill in verbal debate, band wagon effects of majority opinion, and persuasion. [5]

There are also disadvantages to Delphi. Some of these have been pointed out by Ayres and Cetron in their books concerning technological forecasting. [5] [10] These disadvantages include: (1) It is difficult to allow for the bias of the pollster. For example, the framers of the questions can to some degree guide the trend of the answers.

(2) Panel members dislike starting with a blank piece of paper. They also dislike being involved in extensive iterations and evaluating projections outside their areas of expertise. (3) Extensive iterations can result in a heavy investment in time and money to the researcher.

The authors have taken the above mentioned advantages and disadvantages into consideration in deciding to recommend Delphi as an appropriate technique to use in the costing of fiber optics. Primary reasons for the Delphi selection are: (1) Fiber optics is an emerging technology which is fraught with not only technological uncertainties, but also total demand uncertainty. In addition, there are component price uncertainties. (2) The experts in the fiber optics industry can be easily identified (see Appendix E). (3) Users and producers alike would benefit from the results of a Delphi study. It is to their mutual advantage to cooperate in efforts to realize the potential benefits of this emerging technology. (4) Improved forecasts or estimates of future demand quantities, industry growth rates, technological advances and component prices are expected to decrease the range of the estimates for these variables. As a result, the number of scenarios to be developed can be fewer since the range of estimates is smaller. Based on the above

considerations, the authors recommend a Delphic approach. Specifically, the authors make the following recommendations: (1) The first iteration should provide a firm starting point for participants by structuring events into sub-categories of technology, demand quantities, growth rates, and component prices. (2) The number of iterations should be limited to two or three unless further refinement is required. (3) The panelists should be required to self-weight themselves as to their expertise in evaluating events in any given field or sub-category of the questionnaire. These weights should range from 1 (highly qualified) to 5 (not qualified). (4) Construct the Delphi questionnaire format such that there is an interweaving of timing, producer feasibility, and user desirability. Timing is particularly important because of the heavy time dependence of scenarios. The feasibility and desirability aspects are particularly important to the producers and users respectively as they relate to their particular areas of expertise. (5) Panelists should be informed of the study plan and its schedule prior to involvement. They should also receive the final results of the study.

The following Delphi questionnaire, as developed by the authors, is meant to accomplish the above suggestions. It is

an example of how time, desirability and feasibility can be interwoven to form a simple, yet comprehensive, approach to establishing refined estimates for scenarios. The events are representative of the types of questions which should be included by one who conducts a Delphic study of an emerging technology. Any revision of the suggested Delphi questionnaire, due to information not now available, and its application would be an aspect of the economic analysis to be performed by other NPS students and NELC personnel.

PARTICIPANT SELF-RATING ON QUALIFICATIONS TO ANSWER IN AREAS OF INTEREST (1), HIGHLY QUALIFIED TO (5), POORLY QUALIFIED	#	BASIC EVENTS (including assumptions)	User desirability: Necessary - definitely needed now	User desirability: Will be necessary soon	User desirability: Desirable now, but not necessary	User desirability: Will be desirable soon	User desirability: Undesirable now, possibly desired later	User desirability: Cannot forsee any desirability in future	Producer feasibility: Highly feasible - could produce now	Producer feasibility: Feasible - could produce in future	Producer feasibility: Likely to be produced very soon	Producer feasibility: Likely to be produced in future	Producer feasibility: Unlikely, but possible to be produced	Producer feasibility: Cannot forsee possibility of production	Probable timing (Enter the year by which you feel the probability is P that the named event will have occured): $P=.20$	Probable timing: $P=.50$	Probable timing: $P=.90$
(3)	A	(EXAMPLE: AVIONICS COMPUTERS IN MILITARY AIRCRAFT ARE MINIATURIZED TO 1/4 THEIR PRESENT SIZE).			X							X			1985	1992	2000
		------FIBER OPTICS TECHNOLOGY---------															
( )	1	Modular drivers/receivers, utilizing LED & PIN type diodes, etc., are in production and considered as off-the-shelf items. More than two companies are in competition for contracts. No monopolies.															
( )	2	Monolithic integrated optical circuit drivers & receivers are off-the-shelf available. (etc., as in above question).															
( )	3	MULTI-CHANNEL "STAR", etc., type connectors are off-the-shelf available. (etc., as in event 1).															
( )	4	SINGLE CHANNEL TRUNK, "T", CONNECTORS are in production as off-the-shelf items. (etc., as in event 1).															
( )	5	(ETC., FURTHER QUESTIONS OF INTEREST TO THE MAKER OF A DELPHI QUESTIONNAIRE).															

Figure V-1 Sample Delphi questionnaire

	#	EVENT	User desirability						Producer feasibility						Probable timing: Enter the year by which you feel the probability is P that the named event will have occured		
			Necessary - definitely needed now	Will be necessary soon	Desirable now, but not necessary	Will be desirable soon	Undesirable now, possibly desired later	Cannot forsee any desirability in future	Highly feasible - could produce now	Feasible - could produce in future	Likely to be produced very soon	Likely to be produced in future	Unlikely, but possible to be produced	Cannot forsee possibility of production	P=.20	P=.50	P=.90
		------FIBER OPTICS PRICE TO USER------															
( )	6	Multimode fiber-optic cable, low-loss (<50dB/km), designed to meet cable performance requirements (as delineated in Appendix D of this thesis, etc.), purchased in 10,000 foot lots, will cost: (Assume full production mode, several competing manufacturers, etc.)															
		A. 40-50¢/ft (constant 1975 $'s)...															
		B. 30-40¢/ft (constant 1975 $'s)...															
		C. 20-30¢/ft (constant 1975 $'s)...															
		D. 10-20¢/ft (constant 1975 $'s)...															
		E. Other															
( )	7	(ETC., OTHER QUESTIONS CONCERNING COST. EXAMPLES: MODULE DRIVERS/ RECEIVERS, CONNECTORS, SINGLE MODE CABLE, IOCs, ETC.)															

	#	EVENT	User desirability						Producer feasibility						Probable timing: Enter the year by which you feel the probability is P that the named event will have occured		
			Necessary - definitely needed now	Will be necessary soon	Desirable now, but not necessary	Will be desirable soon	Undesirable now, possibly desired later	Cannot forsee any desirability in future	Highly feasible - could produce now	Feasible - could produce in future	Likely to be produced very soon	Likely to be produced in future	Unlikely, but possible to be produced	Cannot forsee possibility of production	P=.20	P=.50	P=.90
		-------FIBER OPTICS APPLICATION------- (operational)															
( )	8	Military aircraft will employ fiber optics as standard items in avionics data link systems.															
( )	9	Military ships will employ fiber optics as standard items in data link systems. Designed for ship-board systems -- not a retrofit. ...															
( )	10	(ETC.)															
( )	11	Signal bandwidth in excess of that now provided by coax/twisted pair wire (i.e., 20 MHz at 300 M) will be necessary for increased data transfer rates, etc.															
( )	12	How much more bandwidth is desired ?															
		A. > 20 MHz															
		B. > 100 MHz															
		C. > 500 MHz															
		D. > 1 GHz															
		E. (other)															

	#	EVENT	User desirability						Producer feasibility						Probable timing: Enter the year by which you feel the probability is P that the named event will have occured		
			Necessary - definitely needed now	Will be necessary soon	Desirable now, but not necessary	Will be desirable soon	Undesirable now, possibly desired later	Cannot forsee any desirability in future	Highly feasible - could produce now	Feasible - could produce in future	Likely to be produced very soon	Likely to be produced in future	Unlikely, but possible to be produced	Cannot forsee possibility of production	P=.20	P=.50	P=.90
		---FIBER OPTICS PRODUCTION (DEMAND)---															
( )	13	Total U.S. production of low-loss (<50dB/km) single mode fiber optic cable will be:															
		A. 1,000,000 feet															
		B. 10,000,000 feet															
		C. 100,000,000 feet															
		D. other															
( )	14	Total U.S. production of multimode (>200 fibers) medium loss (100-500dB/km) cable will be:															
		A. 1,000,000 feet															
		B. 10,000,000 feet															
		C. 100,000,000 feet															
		D. other															

C. EXPERIENCE CURVE

This section will develop experience curve theory and explain how it can be used as a forecasting technique to help predict the cost behavior of products such as fiber-optic cables, drivers (LEDs) and receivers. Experience curve theory should not be confused with the well-known learning curve theory. Learning curve theory predicts cost reductions for two cost elements, labor and production inputs (materials), whereas experience curve theory predicts cost reductions for all cost elements including labor, development, overhead, capital, marketing, and administration. Experience curve theory is much broader a concept that incorporates learning curve theory. To facilitate the development of experience curve theory, the subsequent discussion will explain both theories noting similarities, differences, and the factors which explain both theories.

Both the experience curve and learning curve theories are expressed as cost quantity relationships stating that each time the total quantity of items produced doubles, the cost per item is reduced to a constant percentage of its previous cost. For example, if the cost of producing the 200th unit of an item is 80 percent of the cost of producing the 100th item, and if the cost of the 400th unit is 80 percent of the

200th item, and so forth, the production process is said to follow an 80 percent unit experience or learning curve. Figure V-2 shows a unit curve for which the reduction in cost is 20 percent (i.e., 80 percent of the original cost) with each doubling of cumulative output. The arithmetic plot illustrates that the reduction in cost for each unit is very pronounced for early units. For example, on the 80 percent curve, cost decreases to 28 percent of the original value (100) over the first 50 units. Over the next 50 units, it declines only 5 more percentage points to 23 percent of the first unit cost. A plot of the same relationship on a log-log scale, as shown in Figure V-3, makes the relationship linear and reflects the constant rate of reduction. Log-log plots are used almost exclusively because the straight-line relationship is easier to construct and use for predictive purposes.

The mathematical relationship between cost and quantity for experience curves and learning curves is represented by the power equation:

$$C_n = C_1 n^{-\lambda} \qquad \text{Equation (1)}$$

where: C_1 : is the cost of the first unit

C_n : is the cost of the nth unit

n : is the accumulated units produced (experience)

λ : is the rate at which cost declines with experience (slope of the experience curve).

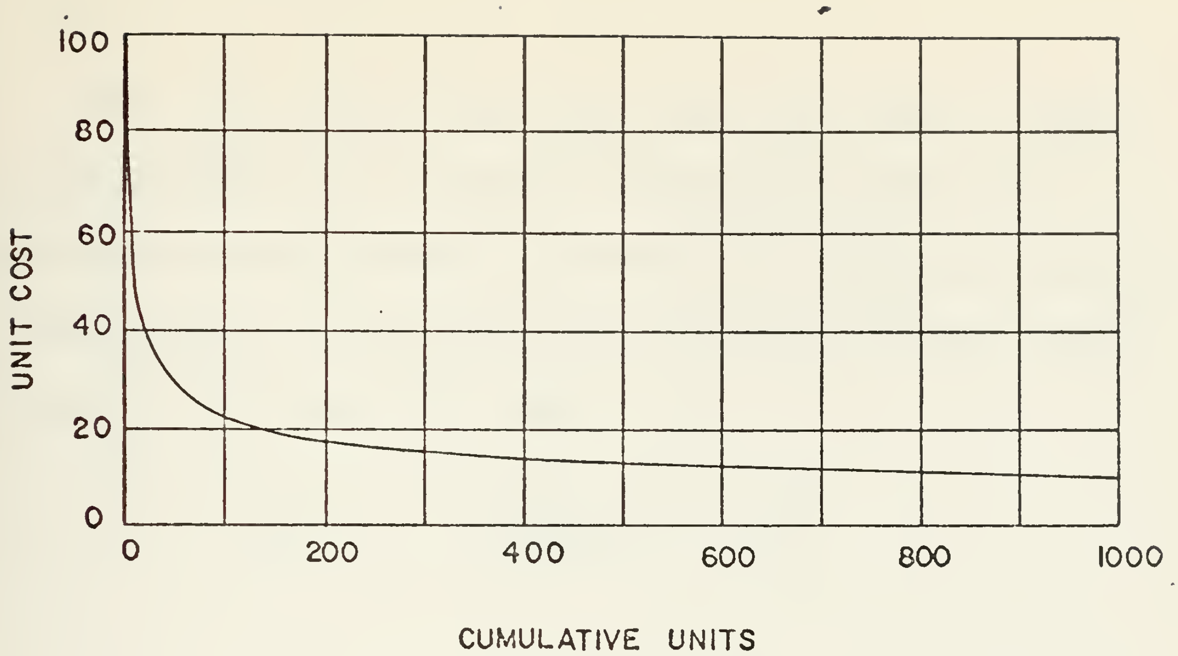


Figure V-2
The 80% experience curve on an arithmetic grid

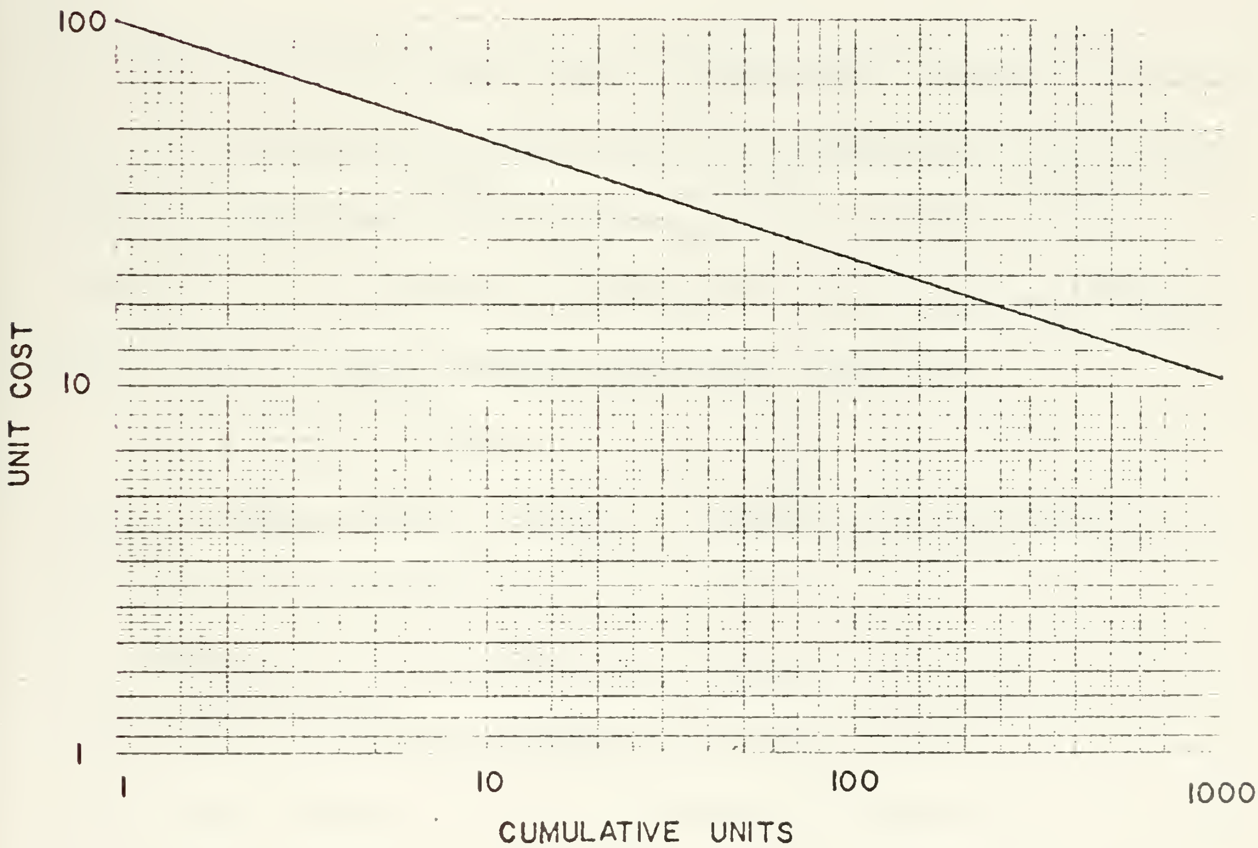


Figure V-3
The 80% experience curve on a logarithmic grid

The slope of the experience curve, λ, bears a simple relationship to the constant percentage to which cost is reduced as the quantity is doubled. By letting S represent the fraction to which cost decreases when quantity doubles, and using Equation (1), then:

$$S = \frac{C_{2n}}{C_n} = \frac{C_1(2n)^{-\lambda}}{C_1(n)^{-\lambda}} = 2^{-\lambda}$$

$$S = 2^{-\lambda} \qquad \text{Equation (2)}$$

$$\lambda = -\frac{\log S}{\log 2} \qquad \text{Equation (3)}$$

For example, an experience curve with a slope of $\lambda = 0.415$ has a constant percentage reduction in cost to 75 percent of its previous cost each time accumulated quantity doubles. In order to avoid confusion, subsequent use of the term "slope" will refer to the constant percentage reduction.

The history of learning curve theory dates back to 1925 when, in the aircraft industry, learning patterns were first observed by the Commander of Wright-Patterson Air Force Base. The phenomonon observed was the constant reduction in direct labor hours required to build airplanes as the number of aircraft built doubled. [21] Subsequently, learning curve theory has been documented and used in many industries to predict

cost reductions for direct labor and raw material -- or production inputs. Typical learning curve slopes have ranged from 75 to 90 percent. Some of the factors commonly mentioned that account for direct labor and material cost reductions are summarized as follows:

(1) Job familiarization by workmen. This results from the repetition of manufacturing operations.

(2) General improvement in tool coordination, shop organization, and engineering liaison.

(3) Development of more efficiently produced sub-assemblies.

(4) Development of more efficient tools.

(5) Substitution of cast or forged components for machined components.

(6) Development of more efficient parts-supply systems.

(7) Improvement in overall management.

(8) Workmen learn to process the raw materials more efficiently, thereby cutting down spoilage and reducing the rejection rate.

(9) Management learns to order materials from suppliers in shapes and sizes that reduce the amount of scrap that must be shaved and cut to form the final product.

The above list of relevant factors is not considered complete. It also tends to understate the importance of the one item usually considered most important -- labor learning. [37]

Experience curve theory dates back to 1965. [9]* Experience curve theory is much broader in scope than learning curve theory. It considers the full range of costs which include development, capital, administration, marketing, overhead, as well as labor costs. Raw material cost is not included in this list. The cost of raw materials usually depends on factors such as availability of supply. For example, the price of unprocessed timber fluctuates from year to year partly as a result of federal policy concerning the nation's timber reserves. Strictly speaking, correct measurement of the experience effect therefore requires that expenditures be calculated net of the cost of raw materials, i.e., on value added to the product. In general, experience curves do not apply if major elements of cost, or price, are determined by patent monopolies, natural material supply, or government regulation. The experience curves apply to products

---

* Experience curve theory is primarily credited to Mr. Bruce Henderson, founder and President of Boston Consulting Group, Inc., a management consulting firm specializing in developing corporate strategy.

in industries with multiple producers who interact rivalously as well as other products in purely and perfectly competitive industries. Experience curves cost reductions on value added range from 20 to 30 percent every time total product experience (accumulated quantity) doubles for an industry as a whole, as well as for individual producers. These reductions represent experience curve slopes of 70 to 80 percent. Empirical data have been collected which verify these experience curve slopes of 70 to 80 percent. Many of these data collection efforts were for products in the chemical and electronics industries. Reports of the Electronics Industry Association, the Manufacturing Chemists' Association, and the 1965 Statistical Supplement to the Survey of Current Business by the United States Department of Commerce, among others, were used in gathering these data, as were Boston Consulting Group sources within the relevant industries. Figure V-4 on integrated circuits and Figure V-5 on polyvinylchloride are two examples illustrating the experience curve effect with the characteristic cost reductions. To permit comparability over time, prices were expressed in constant 1958 dollars.

Price and experience (accumulated quantity) follow one of two characteristic patterns: stable, as shown in Figure V-6, or unstable, as shown in Figure V-7.

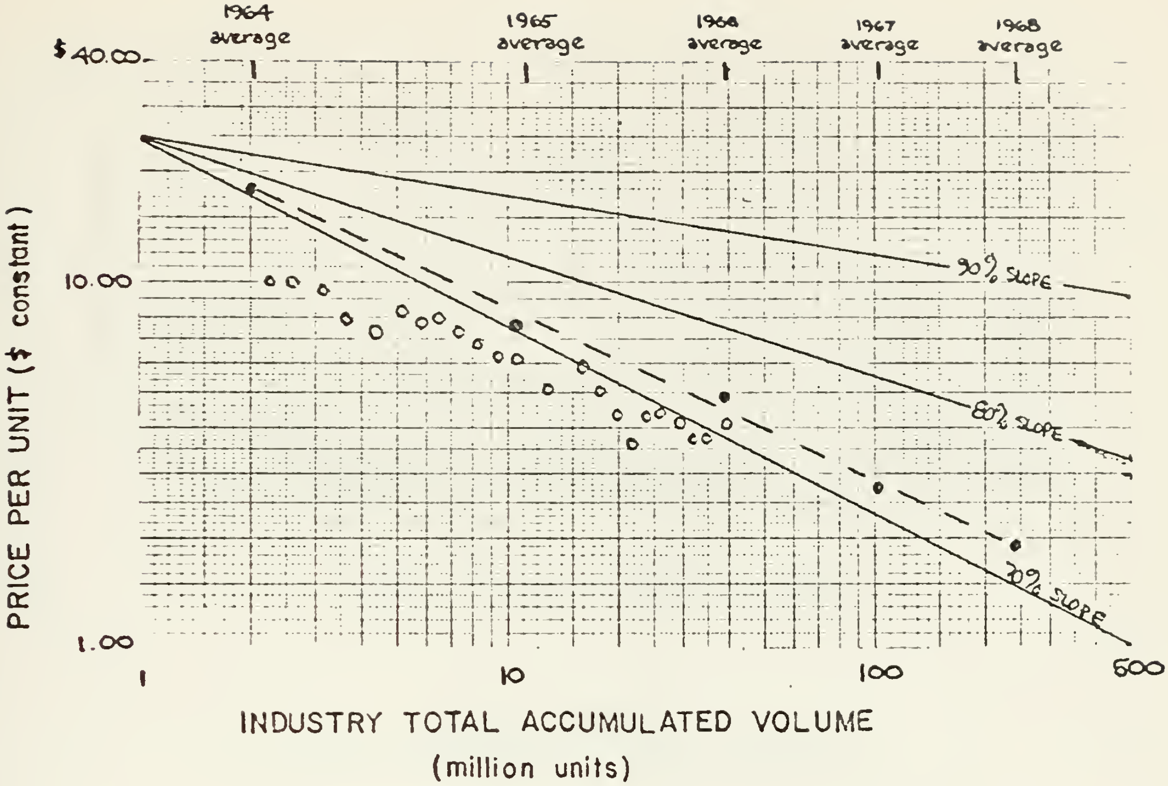
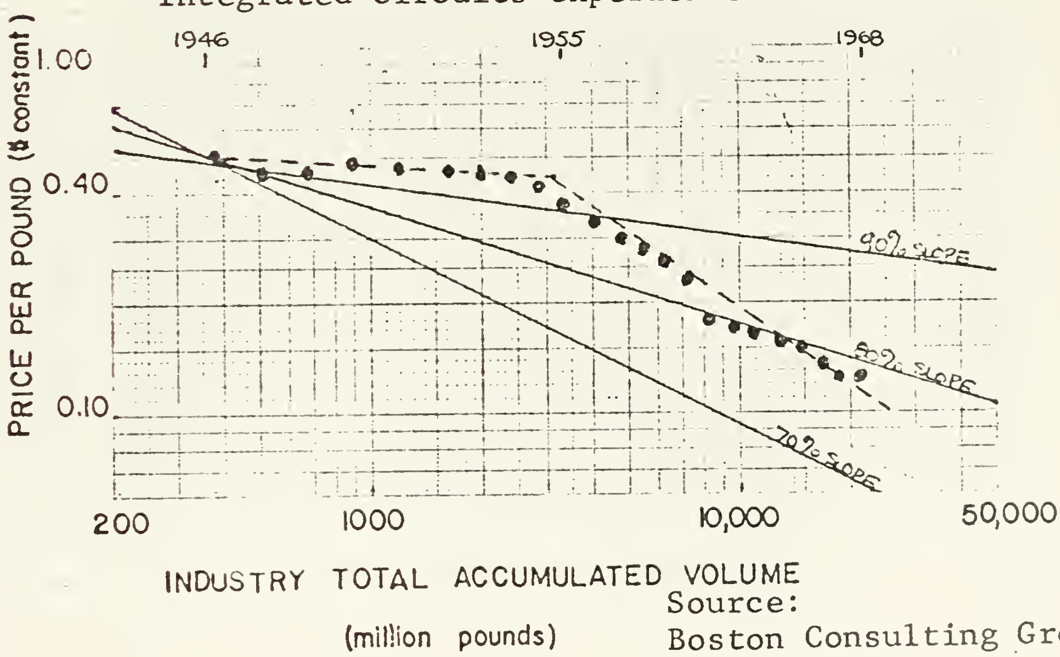


Figure V-4
Integrated circuits experience curve



Source:
Boston Consulting Group

Figure V-5
Polyvinylchloride experience curve

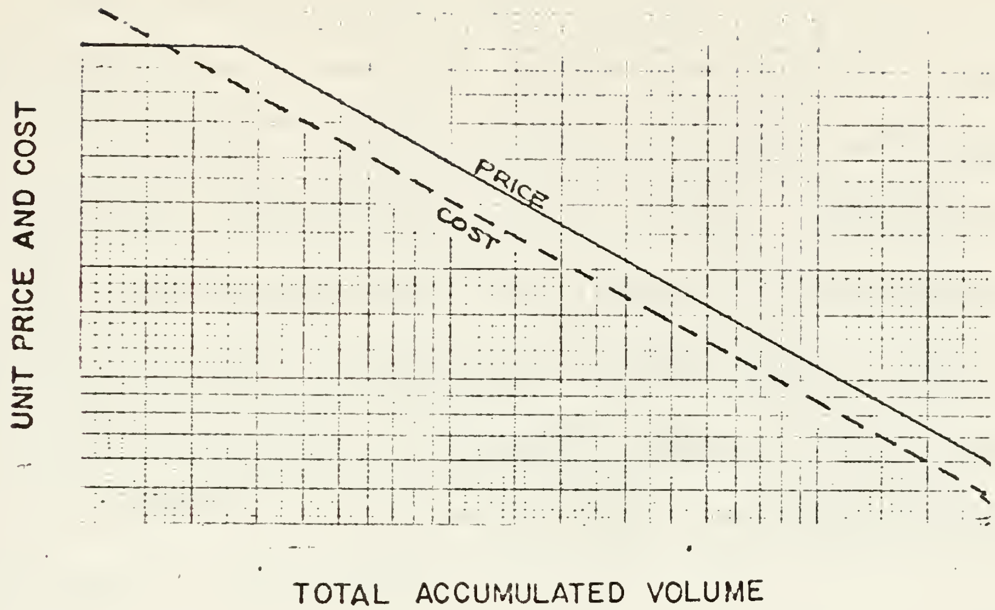


Figure V-6
A characteristic stable pattern

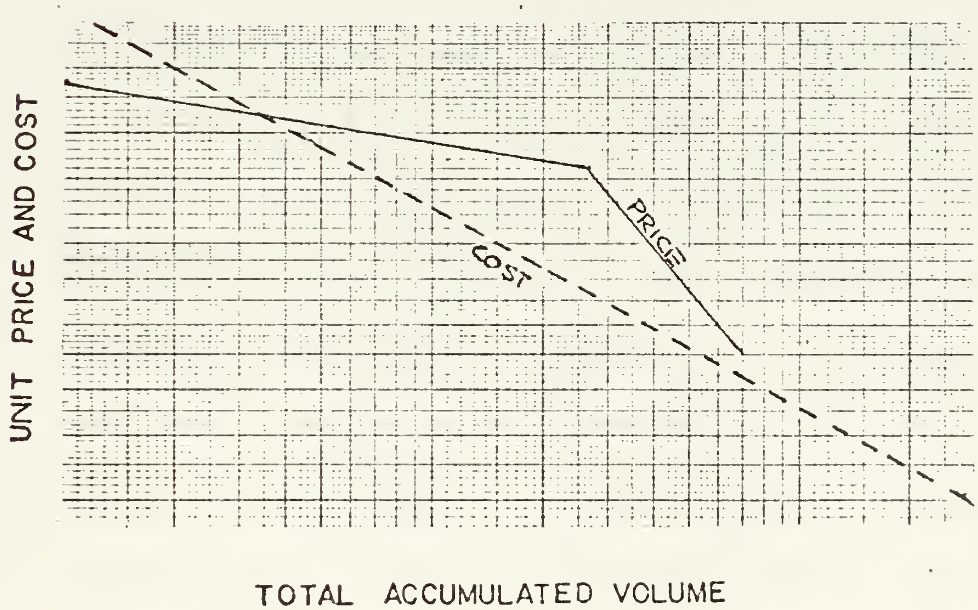


Figure V-7
A typical unstable pattern

A stable pattern exists when the cost and price of a product maintains a constant quantitative difference over time. In Figure V-6, price and cost parallel each other over time thus indicating a stable pattern. Products following this type pattern tend to be found in technological industries which are experiencing rapid growth as well as being very competitive. Integrated circuits is an example of such a product. Its straight-line trend relationship is illustrated in Figure V-4.

When prices do not decline as rapidly as cost, an unstable pattern, as shown in Figure V-7, will exist. Prices are set below cost to establish an initial market. As volume and experience reduce cost, the prices are maintained, gradually converting the negative margin to a positive one. If prices do not decline as fast as costs, then competitors are attracted to enter the market. At some point, prices do start to decline faster than costs. The experience curve for Polyvinylchloride, as shown in Figure V-5, illustrates the point. Obviously, prices cannot decline faster than costs indefinitely. At some point, a reverse bend in the price curve reestablishes a stable relationship between cost and price. Figure V-8 illustrates an unstable pattern transforming to a stable pattern in different phases.

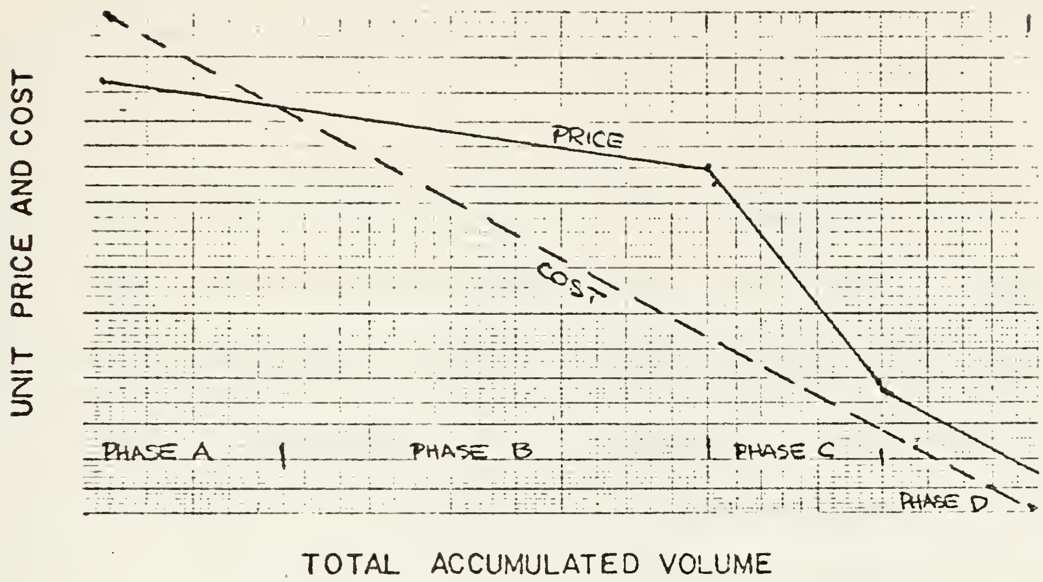


Figure V-8
A characteristic unstable pattern
after it has become stable

In Phase A, costs typically exceed prices. This is always the case in the very early production stages of a new product. It covers an extensive period if the future potential is obvious and competition appears severe in the very early life of the product.

In Phase B, the market leader is effectively holding a price umbrella over higher cost producers who are entering the market and increasing their market share. In effect, the dominant producer is trading future market share for current profits.

Phase C is a shakeout period. This phenomenon is caused when a producer thinks that his own interests will be better served by lowering the price faster than industry costs are declining. The typical slope of the experience curve during this phase is about 60 percent during the period in which industry experience doubles. This, in fact, does not occur unless the cost-price relationship is unstable. An unstable market is characterized by rapid growth, a large number of producers, and a large difference between price and cost for the lowest cost producer. The motivating factor for the lowest cost producer to lower his price is to increase his market share. High cost producers must then either accept lower profit margins or drop out of the industry.

At the end of the shakeout phase, the stability of the relationship of cost to price is fully established and Phase D, i.e., stability, emerges.

The factors, identified by the Boston Consulting Group, that cause the experience curve effect include:

(1) The "learning curve effect"

(2) Competition (rivalry) among producers in a given product market

(3) Economies of scale and specialization; the "scale effect"

(4) Investment in capital to reduce cost and increase productivity.

The learning effect, people learning by doing, has already been discussed in learning curve theory and is the major factor which causes reductions in labor costs. The second factor, competition (rivalry) among producers, forces each producer to find means of lowering his total average costs in relation to his competitors. The successful low-cost producer will then be able to lower his prices and induce a situation which causes a "shakeout" of those producers who have been unsuccessful in reducing costs. This will give the low cost producer an increased market share. With increased market share, the third factor, economies of scale, can be realized. With scaled-up volume due to increased market share, it is possible to use more efficient tools and spread their cost over enough units so that both labor and overhead costs are reduced. Increased volume may also make it possible to consider alternative materials and alternative methods of manufacture and distribution which are uneconomic on a small scale. The final factor, investment in capital, is a further attempt to reduce cost by displacement of less efficient factors of production. This can be accomplished by automating various stages of production thus reducing labor costs. This may not be

possible or desirable if the market share is not sufficient to warrant the investment.

To use the experience curve as a predictive tool the following elements are required:

(1) C_1 - first unit price

(2) Initial experience (accumulated quantity), represented by C_1

(3) The slope of the experience curve.

With these three elements it is an easy matter to construct an experience curve on a log-log plot. As a hypothetical example for low-loss fiber-optic cable, an initial price of $4.00 per foot with an initial experience of 100,000 feet is assumed. Experience curve slopes of 70, 80, and 90 percent are plotted to illustrate a range of cost reductions possible. Figure V-9 illustrates the three experience curves with their different slopes. The initial point (100, $4.) is common to all three experience curves. A second point for the 70 percent curve is obtained by multiplying (.70) (4.00) = $2.80. This $2.80 figure is for the doubled quantity of 200. Hence the second point (200, $2.80) is obtained and a straight line is constructed to complete the curve. The 80 and 90 percent curves are constructed in like manner.

These curves illustrate how prices might decrease as a function of accumulated quantity but they do not indicate when these price/quantity relationships will occur. Time frames can be established if the rate of growth of the accumulated quantity is known. Use of the standard formula for annual compound interest is applicable. The formula is:

$$A = (1.00)\,(1 + i)^{T} \qquad \text{Equation (4)}$$

where: i : is the annual interest rate

T : is the time in years \$1.00 has been invested

A : amount accumulated after T years.

Changing Equation (4) to multiples of accumulated quantity produced and using growth rate in place of interest rate yields the new formula:

$$mA = A\,(1 + g)^{T} \qquad \text{Equation (5)}$$

where: m : is the desired multiple of any accumulated quantity produced

A : accumulated quantity produced

g : annual growth rate of the product

T : years required to attain the desired multiple.

Solving Equation (5) for T provides the desired result:

$$T = \frac{\log m}{\log\,(1 + g)} \qquad \text{Equation (6)}$$

For example, the time to double accumulated quantity ($m = 2$) having a growth rate of 40 percent per year ($g = .4$) is

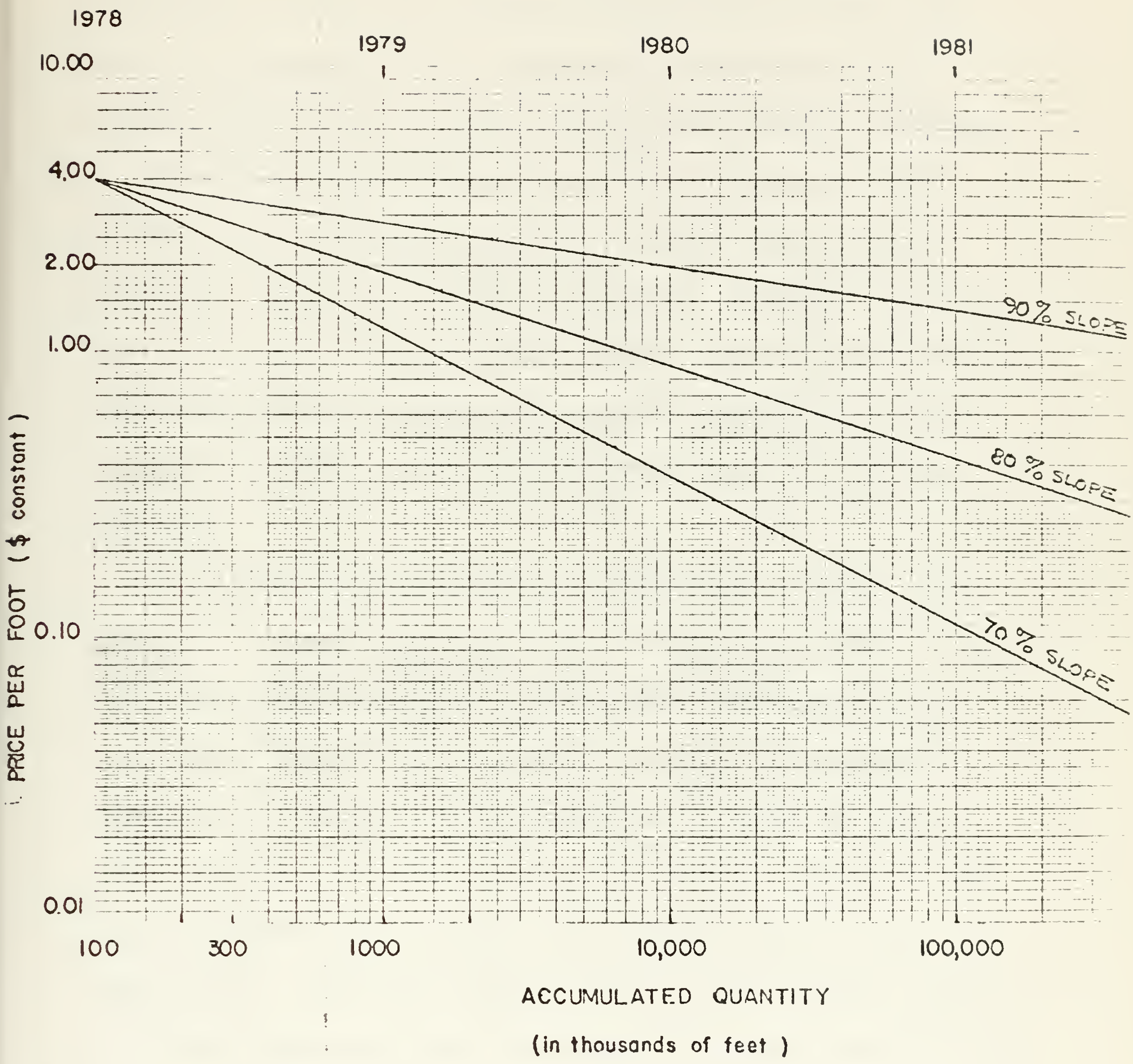


Figure V-9
Hypothetical example of a fiber-optic
cable experience curve

approximately two years. Figure V-9 indicates (hypothetical) a ten-fold increase ($m = 10$) in accumulated quantity each one year interval ($T = 1$). By solving Equation (6) for growth rate an annual growth rate of 900 percent is obtained.

Experience curve theory then offers a means of fore-casting price reductions for well-defined (standardized) products. Again, to use this technique, estimates of first unit cost and a production base (initial accumulated quantity) associated with the first unit cost are required. If time frames are desired, estimates of growth rate must also be provided.

Since most of this required information is either non-existant, or available only on a prototype development basis, the authors have suggested constructing scenarios of the fiber-optic industry's alternative futures. The example scenarios in Section IV were developed in terms of fiber-optic component evolution and standardization, military and civilian demand requirements, and possible growth rates that might occur. Scenarios thus provide the information required to use the experience curve technique to predict cost of fiber-optic system components such as cable, drivers (LEDs) and receivers. These component cost estimates could then be used as inputs to the life cycle cost model.

VI. SUMMARY AND CONCLUSIONS

This thesis contains the results of the initial cost-effectiveness investigation of the fiber-optic alternative for an avionics data link system. The study was intended as an initial approach toward the desired objective of numerical estimation of fiber optics avionics data link life cycle costs.

The historical and technological background of fiber optics as well as the background of the A-7 ALOFT Demonstration was discussed. A general discussion of a cost-effectiveness analysis was presented together with possible measures of effectiveness for data link systems.

Scenario-writing was discussed as a means of ordering the uncertainties of this emerging technology. Sample scenarios were developed by the authors to provide specific time-related estimates as to civilian/military demand, growth rates, standardization and technological development in fiber optics. These representative scenarios are meant to be examples of scenarios which can be established as a base for making cost estimates.

Two specific forecasting techniques, Delphi and experience curves were discussed as relevant to the costing of this

emerging fiber optics technology. A Delphi questionnaire is proposed as a means of soliciting forecasts from a panel of experts in order to deal with the specific uncertainties associated with fiber optics. Experience curves were suggested as a means of predicting the cost behavior of products such as fiber-optic components.

It is the basic conclusion of the authors that: (1) These techniques, scenario-writing, Delphi and experience curves, can be combined as a cost-predictive method to estimate component prices in an emerging technology such as fiber optics. (2) Meaningful component cost predictions can then provide a means of estimating reliable costs for the life cycle cost model elements used in a cost-effectiveness study. (3) At the present time, the uncertainties associated with future cost estimates of fiber-optic components, uncertainties of demand and production, and lack of standardization will require careful analytical work if reasonably accurate life cycle cost estimates are to result. (4) The emerging fiber optics technology deserves full and continuing effort and attention by R&D agencies. Even if the results of initial cost-effectiveness studies are such that the decision is made to <u>not</u> use fiber optics

in next generation aircraft, it would be a mistake to cut back or reduce fiber optics R&D funding. Future military communication and data link systems may well be the beneficiaries of today's development efforts.

<u>APPENDIX A</u>

A-7 Navigation Weapons Delivery System (NWDS) Schematics

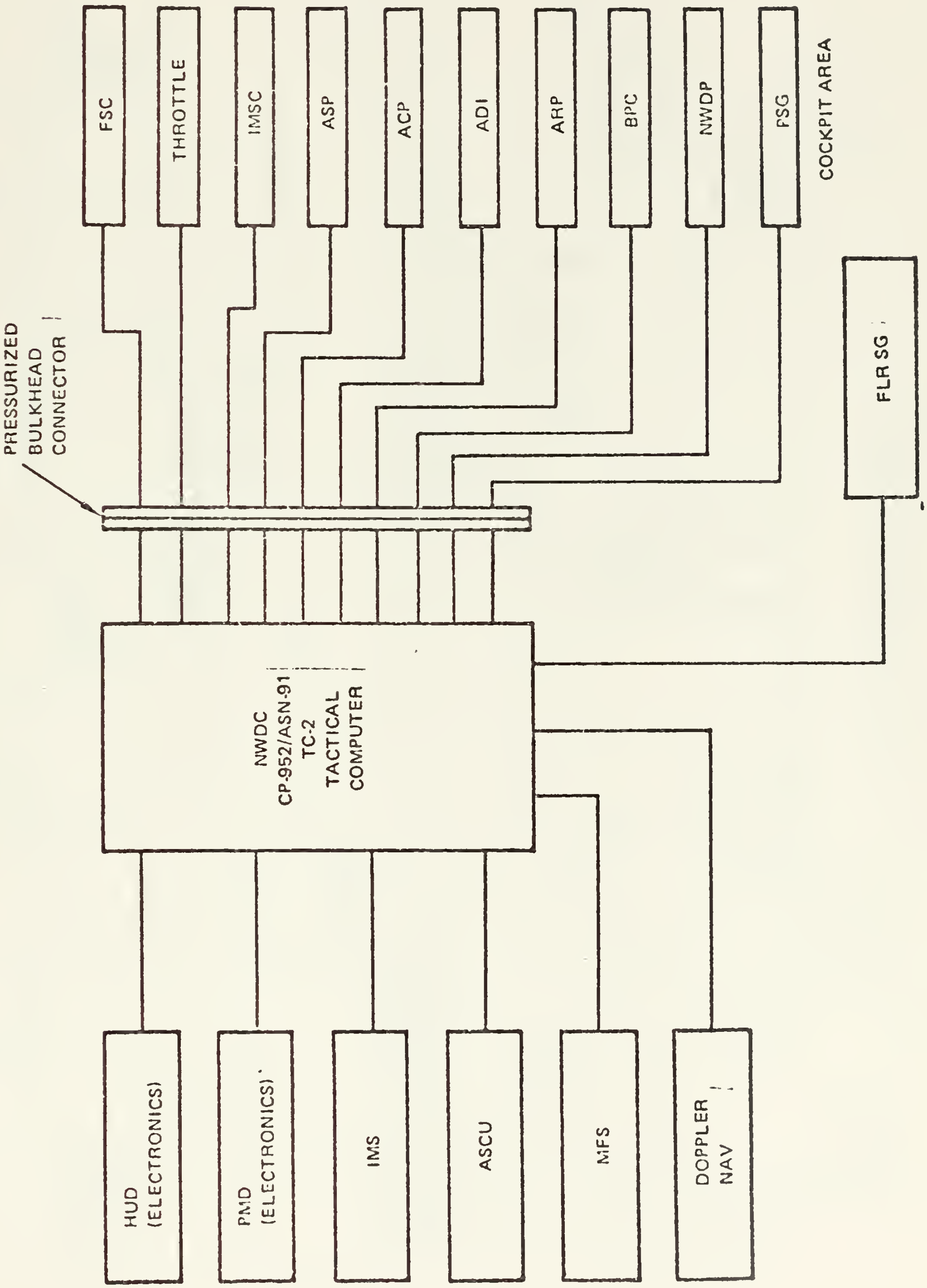


Figure 1. A-7 N/WDS electrical interface

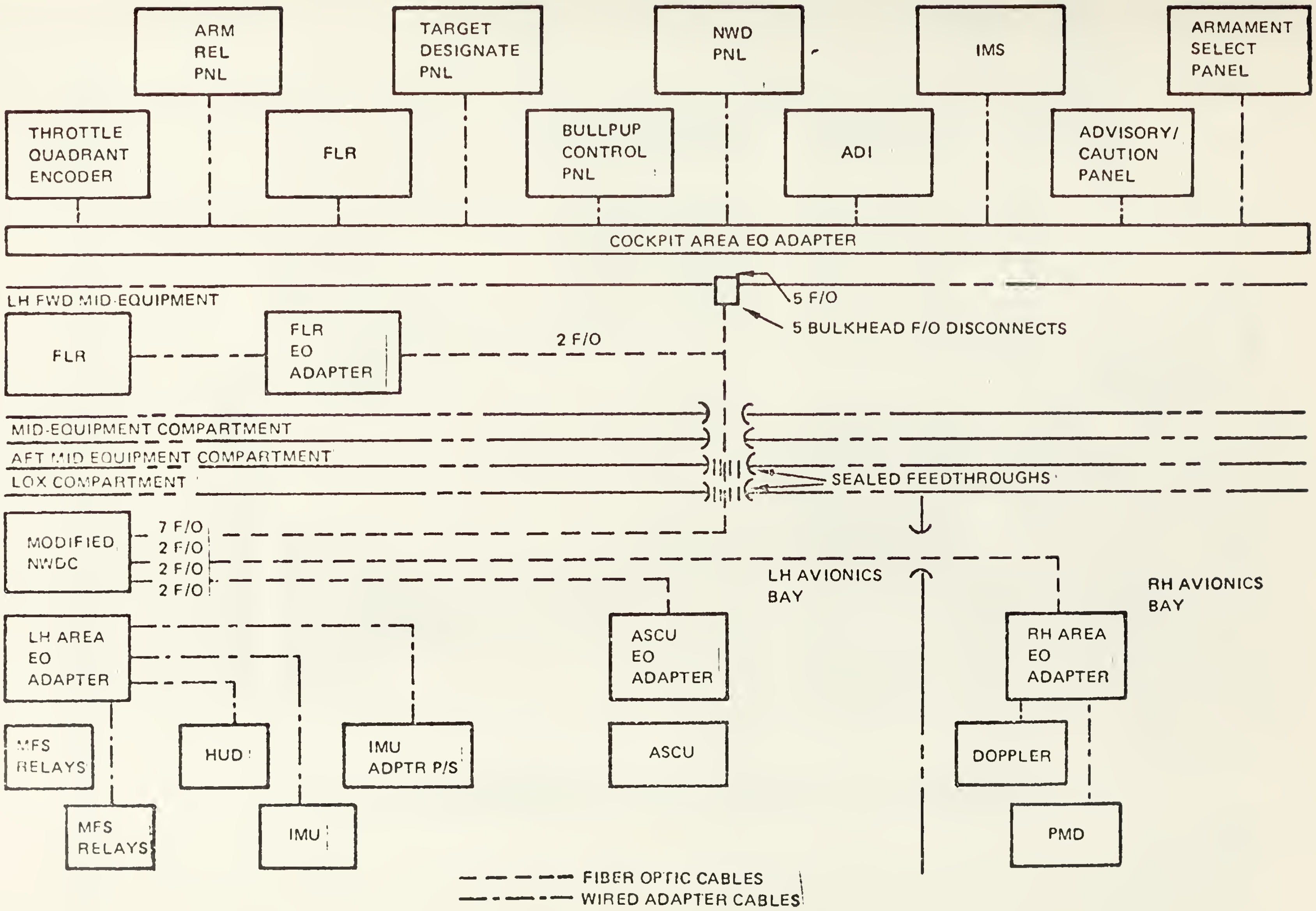


Figure 2. A-7 ALOFT system configuration.

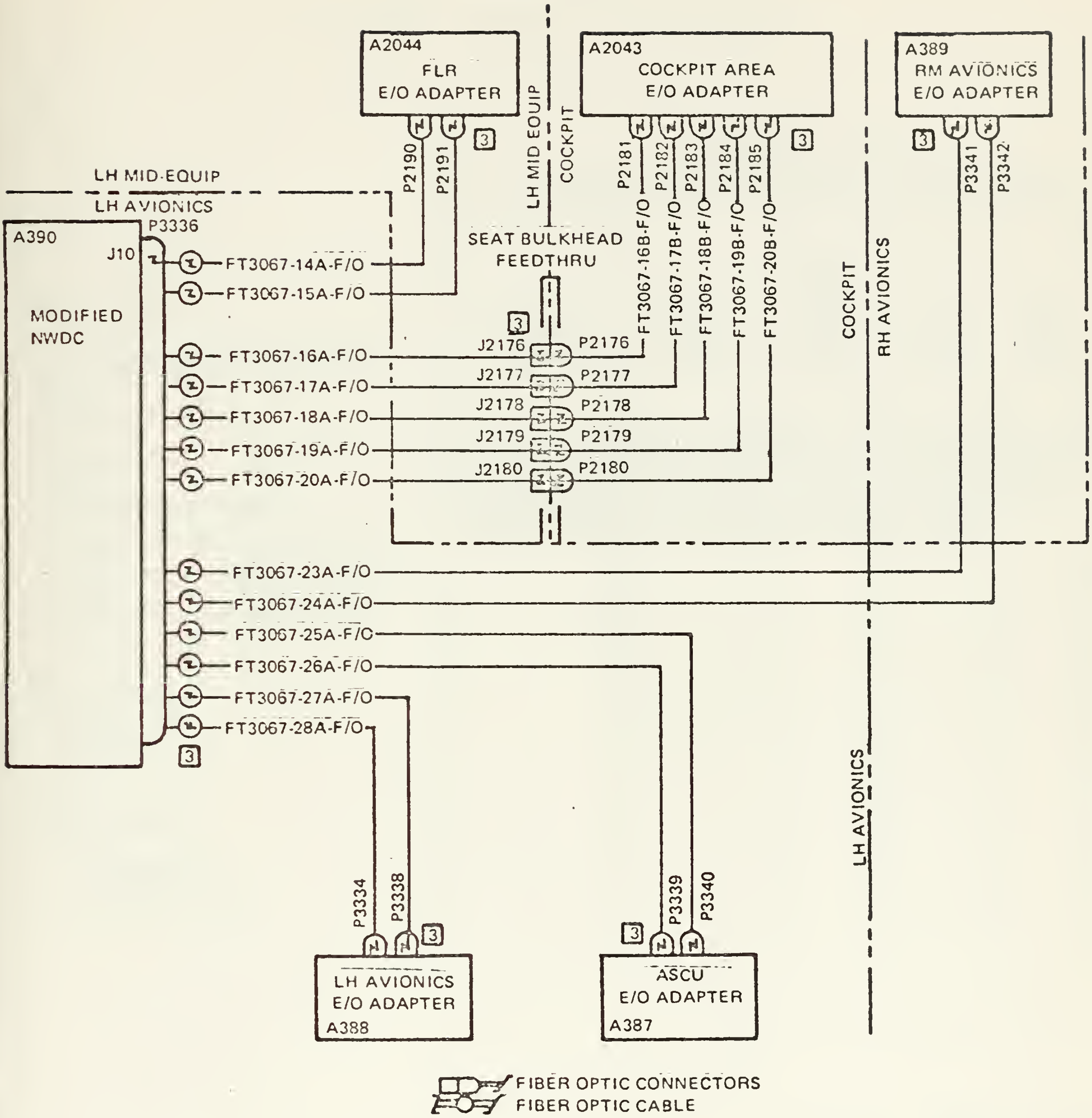


Figure 3. A-7 ALOFT fiber optic interface configuration.

APPENDIX B

A-7 ALOFT Component Requirements

	A. ORIGINAL SYSTEM (PORTION CONTAINED IN ALOFT CONFIGURATION)					
Type of Components Required	No Required Footage	Unit Cost (FY75) ($)	Total Cost (FY75) ($)	Unit Wt (gm)	Total Wt (lb)	Total Power Consumption (W)
1. Single Cables/Wiring						–
	These data to be derived and provided at a later date by LTV and IBM through analysis of the quantities, cost, weights, and characteristics of the components that are used in the existing A-7 N/WDS design to originally transmit the 115 unmultiplexed ALOFT signals.					
2. Signal Connectors						
a. Single-channel bulkhead						–
b. Single-channel pressure bulkhead						–
c. Multichannel bulkhead or rack/panel						–
d. Multichannel pressure bulkhead						–
e. Access couplers						
3. Signal Drivers						
a. LEDs						
b. Drive circuitry						
4. Signal Receivers						
a. Photodetectors						
b. Amplifier circuitry						

Source: NELC TD 435

Type of Components Required	B. TWISTED PAIR – AFTER MULTIPLEXING						
	Perform Req or Part No	No Required (footage) ($)	Unit Cost (FY75) ($)	Total Cost (FY75) ($)	Unit Wt (gm)	Total Wt (lb)	Total Power Con-sumption (W)
1. Single Cables/Wiring							
2. Signal Connectors							
a. Single-channel bulkhead	Determined to be infeasible with presently available twisted-pair components at 10-Mbit data rates and within MIL-E-5400P Class II Aircraft Environment.						
b. Single-channel pressure bulkhead							
c. Multichannel bulkhead or rack/panel							
d. Multichannel pressure bulkhead							
e. Access couplers							
3. Signal Drivers							
a. LEDs							
b. Drive circuitry							
4. Signal Receivers							
a. Photodetectors							
b. Amplifier circuitry							

Type of Components Required	C. COAX – AFTER MULTIPLEXING						
	Perform Req or Part No	No Required (qty/footage)	Unit Cost (FY75) ($)	Total Cost (FY75) ($)	Unit Wt (lb or gm)	Total Wt (lb)	Total Power Con-sump-tion (W)
1. Single Cables/Wiring	RG-316	13 (225 ft)	0.30/ft	66.08	0.012/ft	2.7 lb	–
2. Signal Connectors							
a. Single-channel bulkhead	Sealectro 50-622-9188-31	36	3.27 ea	117.72	3.371g ea	0.21 lb	–
	50-645-4576-31	26	3.27 ea	85.02	2.320g ea	0.13 lb	
b. Single-channel pressure bulkhead	Sealectro 50-675-7000-31	5	8.34 ea	41.70	4.34g ea	0.05 lb	–
c. Multichannel bulkhead or rack/panel	–	0	No multichannel coax connectors considered feasible for this application. Single channel utilized instead with printed circuit board connectors.				–
d. Multichannel pressure bulkhead		0					
e. Access couplers	–	0	–	–	–	–	–
f. Printed circuit-board	Sealectro 50-651-0000	26	4.46 ea	115.96	2.320g ea	0.133 lb	–
3. Signal Drivers	SN54S140	13	6.26 ea	81.38		0.004 lb	0.286
a. LEDs	–	–	–	–	–	–	–
b. Drive circuitry	–	–	–	–	–	–	–
4. Signal Receivers	SN54S132	13	13.28 ea	172.64	ea		0.585
a. Photodetectors	–	–	–	–	–	–	–
b. Amplifier circuitry	–	–	–	–	–	–	–

Type of Components Required	D. FIBER OPTICS – AFTER MULTIPLEXING						
	Perform Req or Spec No Part No	No Required (qty/footage)	Unit Cost (FY75) ($)	Total Cost (FY75) ($)	Unit Wt (lb or gm)	Total Wt (lb)	Total Power Consumption (W)
1. Single Cables/Wiring	See NELC Performance Requirements Sheets in appendix A for description of required components	13 (225 ft)	2.50/ft	562.50	6.94/ft	3.42	–
2. Signal Connectors							
a. Single-channel bulkhead		13	2.50 ea	32.50	13.56g ea	0.389 lb	–
b. Single-channel pressure bulkhead		5	3.50 ea	17.50	22.79g ea	0.251 lb	–
c. Multichannel bulkhead or rack/panel		1	500.00 ea	500.00	255.00g ea	0.562 lb	–
d. Multichannel pressure bulkhead		0					
e. Access couplers		0					
3. Signal Drivers		13 (12 digital & analog					4.45
a. LEDs		a. 14*	80.00 ea	1120.00	**	**	–
b. Drive circuitry		b. 12 digital 1 analog	2.50 ea 32.00 ea	30.00g 32.00g	0.085 lb 0.027 lb		– –
4. Signal Receivers		13 (12 digital 1 analog)	–	–	–	–	6.31
a. Photodetectors		a. 14*	38.25	535.50	**	**	–
b. Amplifier circuitry		b. 12 digital 1 analog	50.84 31.85	610.08 31.85	17.5g 16.25g	0.463 lb 0.036 lb	– –

*The one analog link in the ALOFT design requires two LEDs: one direct signal transmission and one for feedback for linear compensation. Therefore, the transmission over 13 data channels requires 14 LEDs and 13 photodetectors.

**The weight figures for driver circuitry and amplifier circuitry include the weights of the LED and photodetector, respectively.

APPENDIX C

A-7 ALOFT Component Descriptions

Description of Components Required as Building Blocks for a Point-to-Point Information Transfer System of 115 digital signals (A-7 ALOFT baseline):

A. Coax Interface System Components Requirements (assuming digital transmission only over 13 data links – no analog). Prices in quantities (FY75 prices).

1.0 CABLE. Type RG316

Spec: (Description) 50Ω, 0.102″ OD, 29.4 pF/ft, loss = 3.8 dB/100 ft @ 10 MHz,
temp = –55 to +200°C

Requirement: 225 feet

Price: $293.70 per 1000 feet; $66.08 total system cost

Weight: 0.012 lb/ft; 2.7 lb total system

2.0 CONNECTORS

2.1.1 Terminal Connectors. Type Sealectro 50-622-9188-31. All connector prices subject to 10-percent gold surcharge

Spec: Crimp type coax connector – straight plugs for RG316. All connector specs MIL-C-39012 SMA

Requirement:	2 ea for each cable link (13)	26
	2 ea for each bulkhead connector =	10
	Total	36 each

Price: $3.27 each; $117.72 total system cost

Weight: ~3.371g each

2.1.2 Bulkhead Receptacles. Type Sealectro 50-645-4576-31

Spec: SMA receptacle MIL-C-39012

Requirement: 26 each (on each adapter unit, 2 for each cable)

2.2 Pressure Bulkhead Connectors. Type Sealectro 50-675-7000-31

Spec: MIL-C-39012 SMA

Source: NELC TD-435

Requirement: 5 each

Price: $8.34 each/$41.70 total

Weight: ~4.340g each

2.3 No multichannel connectors.

2.4 PC Card to Coax Connector. Type Sealectro 50-651-0000

Spec: MIL-C-39012 SMA

Requirement: 26 each

Price: \$4.46 each/\$115.96 total

Weight: ~2.320 grams

3.0 LINE DRIVERS. Type SN 54S140

Spec: Dual line drivers, 50Ω, Schottky for operation at 10 MHz

Requirement: 13 each (assume only one gate used per IC)

Price: \$6.26 each/\$81.38 total

Power: 22 mW ea/gate; 0.286W total

Weight: ~ 1.973 grams each

4.0 LINE RECEIVERS. Type SN 54S132

Spec: Quad Schmitt trigger

Requirement: 13 each

Price: \$13.28 each/\$172.64 total

Power: 45 mW ea gate; 0.585W total

Weight: ~ 1.973 grams each

B. Twisted-Pair Interface System Components Requirements

Conclusion reached after searching for qualified components that twisted-pair interface not possible. Components for 10-megabit data rate did not readily exist. RG-108 could have been used if constraint of MIL-E-5400P Class 2 environment had not been a requirement. RG-108 is only good for –40 to +80°C temperature range which is below Class 2.

C. Fiber Optic Interface System Components Requirements

1.0 FIBER OPTIC CABLE PERFORMANCE REQUIREMENTS

1.1 Number of fibers: 367 – 1 percent (4)

1.2 Number of broken fibers: four if unterminated; seven if terminated

1.3 Fiber diameter: 0.00215 inch

1.4 Core glass area to total fiber area ratio: ⩾85 percent

1.5 Numerical aperture: between 0.54 and 0.67

1.6 Maximum optical attenuation: 400 dB/km

1.7 Cable jacket and shield to be nonmetallic

1.8 Termination diameter: if terminated, active area diameter to be 0.0455 inch

1.9 Termination loss: without lenses or refraction matching, throughput loss to be <2.0 dB

1.10 Environmental range: temperature, temperature shock, vibration, mechanical shock, and altitude capabilities to conform to MIL-E-5400P Class 2

1.11 Mechanical requirements: impact, bending, and twisting to conform to MIL-C-13777F

1.12 Tensile strength: 35 lb

2.0 SIGNAL CONNECTOR PERFORMANCE REQUIREMENTS

2.1 Fiber Optic Cable: Fiber optic cable used with connectors to be as required in performance requirements for fiber optic cable

2.2 Termination Diameter: Connector termination for fiber optic cable to be 0.0465 (+0.001) inch diameter

2.3 Cable Retention: Connector retention to exceed breaking strength of glass

2.4 Optical Loss: Maximum optical throughput loss to be ≤2.75 dB measured at 800 to 950 nm

2.5 Environmental Requirements: Temperature, temperature shock, vibration, mechanical shock, and altitude capabilities to conform to MIL-E-5400P Class 2

2.6 Connector Durability: All requirements met after 1000 cycles of mating and unmating

2.7 Pressurization: Connectors designed for use as pressure bulkhead penetrators to meet pressurization requirements of MIL-E-5400P Class 2. Also to maintain required gage pressure of 30 (±5) psi during steps 2 and 12 of MIL-T-5422 for Class 2 operation

2.8 Requirements apply to single-channel and multichannel connectors

3.0 DIGITAL SIGNAL DRIVER PERFORMANCE REQUIREMENTS

3.1 Electrical: Input to ITTL load; power supply to be 5.0 (±0.5) Vdc

3.2 Optical Output: Optical half-power points to be 50 nm apart and within range of 800 to 950 nm

3.3 Power Coupling Ability: 1.25 mW into 45-mil-diameter fiber optic cable

3.4 Logic Code: 1.25 mW into 45-mil cable at application of high TTL input; ≤0.01W into 45-mil cable at application of low TTL input

3.5 Pulse switching time: ≤10 ns

3.6 Environmental Characteristics: Operate in all conditions of MIL-E-5400P Class 2 environment

3.7 Operation Lifetime: 10 000 hours continuous at 25°C

4.0 DIGITAL SIGNAL RECEIVERS

4.1 Responsivity: Platform 600 to 1100 nm

4.2 Power Supply: +5 (±0.5) Vdc and –5 (±0.5) Vdc

4.3 Transfer Characteristics: Convert input optical signals to standard TTL output format with fanout of 10. See following table:

Radiant Power Input (watts)		Power Supply (Vdc)	Electrical Output	
Min	Max		Min	Max
4×10^{-7}	2×10^{-4}	+5 (±0.5)	2.7 V @ 1-mA output current	
	2×10^{-8}	–5 (±0.5)		0.5 V @ 16-mA output current

4.4 Electrical Output Switching Time: ⩽10 ns

4.5 Environmental Characteristics: Operate in all conditions of MIL-E-5400P Class 2

4.6 Operation Lifetime: 10 000 hours continuous at 25°C

APPENDIX D

Fiber Optics Cost Data Collection

Mfg	Loss	Dia (active)	Packing Fraction	NA	Fiber Dia.	No. of Fibers	Price/ft.
Galileo K2/K	0.15 dB/ft (457 dB/km) (0.21 dB/ft) (measured) [87m or 266ft/40dB]	45 mil, 1.125 mm	0.75	0.66			$2.50 mono-coil/pvc
American Optical M-80	0.122 dB/ft (372 dB/km) [108m or 328ft/40dB]	50 mil, 1.25 mm	0.80	0.55			$3.75 mono-coil/vinyl
Valtech	0.20 dB/ft (610 dB/km) [65m or 200 ft/40dB]	53 mil, 1.325 mm	0.88	0.56			$2.65 mono-coil/pvc (with termination)
Corning	6.5 dB/1000 ft (20 dB/km) [2km or 6096 ft/40dB]					7 19 37 61	$ 7/ft 19/ft 37/ft 61/ft ($1/ft/fiber)
Pilkington	0.033 dB/ft (100 dB/km)		0.85	0.50			(<300 m, <900 ft.)(>2.5 km)
100A		30.4mil 0.76mm	--		85mm	61	? ?
100B		23.2mil 0.58mm	(Refractive Index difference 0.048)		65mm	61	3.10ft 2.30ft
100C		18 mil, 0.45mm			65mm	37	2.22ft 1.76ft
100D		12.8mil 0.32mm			65mm	19	1.37ft 1.00ft

Preliminary Data Sheet on Fiber-Optic Cable Costs
Source: T. Meador, NELC

Manufacturer and Part #	P_{out} at 50 MA	V_f at 50 MA	Emission pattern Characteristics	Distance Emitting surface to exit	Emitting Area	Price	Comments
TI SL1282	600 μw	1.5Vmax	Lambertian		$63mm^2$/18 mil dia	$22.00	T1XL 12 packa
SL1314-5	600 μw	1.5V	.5 mw in 23° half angle		"	$21.00	T1L23,24 pack
TIXL 471	1.0 mw	1.5	Lambertian	5 mils	"	$35.00	
Spectronics							
SE1527	1.7 mw	1.5	>50% of power is in 25° half angle cone	30 mils	$63mm^2$/18 mil dia	$29.50	
SE1775	1.7 mw	1.5	>75% of power is in 25° half angle cone	50 mils	"	150.00	
Meret							
TL-25	1.0 mw	1.3	150° Lambertian	50 mils	20 mil sq	$9.40 + set up $ for package	Chopped TO-5 or 18; no se up for non-hermetic

Preliminary Data Sheet on LED Costs
Source: T. Meador, NELC

Device	Active Area(mm^2)	Irradiance Resp. at .910 μm A/W	Idc at 5V	C_{junct} at 5V	Distance Active Area to Radiance Entrance	Package	Reverse Breakdown Voltage	Cost/unit (50 units)
H. P.								
5082-4207	.8/40 mil dia	.25 A/W	<2500pa	6pf	75 mil	TO-18	20V	$ 36.30
UDT								
PIN 3D	50 mil dia	.26 A/W	20na	20pf	90 mil	TO-46	50V	9.65
PIN 040B	.8/40 mil dia	.26 A/W	4na	20pa	80 mil	TO-18	25V	18.00
Inotech								
PD050F	50 mil^2	.26 A/W	15na	7pf		TO-18	20V	10.00
EG+G								
SGD-040	.8/40 mil dia		<10na	<3pf	90 mil (A) 150 mil (B)	TO-5 (A) TO-46 (B)	200V	15.00 (A+B)
Motorola								
MRD510		.25 A/W	250pa	<4pf	180 mil	TO-18	100V	
Spectronics								
SD5425-1		.5 A/W	<20na	<4pf	185 mil	TO-46	75V	4.00
SD5425-2		.5 A/W	<20na	>4pf			200V	8.65
SPX1615	50 mil dia	.5 A/W	< 1na	>2.5pf		TO-46	>200V	22.00
Monsanto								
MDL	.58/34 mil dia	4.0MA/mw/cm^2	200na	15pf	> 150 mil	TO46	50V	5.35
TI								
TIXL 80	.8/40 mil dia							NA

Preliminary Data Sheet on Silicon Photodiode Costs
Source: T. Meador, NELC

Company	Quantity of Fibers in Bundle	Bundle Diameter (inch)	Attenuation (dB/km)	Cost ($/ft)
Galileo	High Loss:			
	300	0.045	750+	0.11
	2,000	0.125	750+	0.82
	Medium Loss:			
		0.035	400	0.75
		0.125	400	3.00
Corning	High Loss:			
		0.087	1,000	.35
		0.120	1,000	.69
		0.129	1,000	.92
		0.139	1,000	1.15
	Low Loss:			
		0.050	30	17.50

A Comparison of Commercially Available
Multimode Fiber-Optic Cable
Source: Army REPORT EMCOM-4271 by CW3 Richard D. Parent
Nov. 1974

	ITEM DESCRIPTION	PRICE
1	P.V.C. Jacketed 35 mil dia fiber-optic cable	$0.75/ft
2	End terminator for TO 18 Mating	50.00
33	End terminator for TO 5 Mating	50.00
4	Hybrid, TO packaged, receiver in connector	400.00
5	Hybrid, TO packaged, transmitter in connector	350.00
6	Complete 100-foot long Hybrid System (Complete fiber-optic data transfer system including: end connector with LED, end connector with photodiode and amplifier, and 100 feet of 15 dB/km fiber-optic cable. This does not include power requirements.)	900.00
7	LED mounted in TO 18 size connector	50.00
8	SPD mounted in TO 18 size connector	50.00

Cost Breakdown of a Fiber-Optic Data Transfer System
manufactured by Galileo Electro Optics Corporation,
Galileo Park, Sturbridge, Mass., 0158
Source: Army REPORT EMCOM-4271 by CW3 Richard D. Parent
Nov. 1974

General Cost Information

COMPONENT			SOURCE
Fiber-optic cable	1.	The Valtech Corporation revealed in August 1975 that they have developed a commercially available 40 dB/km fiber-optic cable with 1 to 40 fibers. Prices range from $2/ft for the single fiber cable to $12.	Telephone conversation with LCDR JOHN ELLIS, Code 1640, NELC, 9-2-75
	2.	NELC accepted delivery of medium-loss (590 dB/km) multimode (367 fibers) fiber-optic cable at a cost of $2.50/ft. This is the cabling to be used in the A-7 ALOFT Demonstration.	Telephone conversation with LCDR JOHN ELLIS.
	3.	Galileo's K2K medium-loss (<500 dB/km) multimode cable is selling at $0.75/ft. Lower prices would be considered for quantity purchases of 100,000 ft.	Telephone conversation with Mr. Rodney Anderson, Galileo, 8-18-75
	4.	Corning's single mode (7-single mode fibers per cable) cable, CORGUIDE, is selling for $13.50/meter, or about $4.11/ft.	Telephone conversation with Mr. Robert Freiberger, Corning Glass Works, 8-18-75
Drivers/ Receivers	1.	Discrete circuit drivers/ receivers for the A-7 ALOFT Demonstration cost approximately $110-120 each.	NELC TD-435
	2.	NELC has awarded a contract to Sperry Univac for the delivery of 60 Hybrid module receivers at a cost of $54,000 (i.e., $900 each). NELC has the option to obtain an additional 30 receivers at $285 each.	Telephone conversation with LCDR JOHN ELLIS, 2 September 1975
Connectors	1.	The ITT Cannon 13-channel bulkhead connector cost was $500 each (6 made). Subsequent cost has been reported as $50 each (unconfirmed).	Telephone conversation with LCDR JOHN ELLIS
	2.	Sealectro has provided NELC with single-channel bulkhead connectors at $2.50-3.50 each for use in the A-7 ALOFT Demonstration	NELC TD-435

APPENDIX E

Industry Contacts for Fiber Optics Components

NELC contacted the following list of manufacturers by mail or telephone. The representatives on this list were considered to have candidate components for the A-7 ALOFT demonstration. Some manufacturers do not appear on the tables in the text because their component seemed unlikely to exhibit the desired performance. Omission from the following list means only that there was no response from the manufacturer to an initial contact by NELC.

Source: NELC TD-426

FIBER OPTIC CABLES

American Optical Corp 14G Mechanic Southbridge, MA 01550	Walt Sigmund	(617) 875-9711
Ealing Optics Corp 2225 Massachusetts Ave Cambridge, MA 02140	Henry Murphy	(617) 491-5870
Edmund Scientific Co 101 E. Gloucester Pike Barrington, NJ 08007		(609) 547-3488
Fiberphotics 2257 Soquel Dr Santa Cruz, CA 95060	Bill Zinky	(408) 475-5242
Galileo E/O Corp Galileo Park Sturbridge, MA 01518	Rod Anderson	(617) 347-9191
Corning Glass Works Corning, NY	Rich Cerney Bob Freiberger	(607) 974-8788
ITT Electro-Optical Products Division Box 7065 Roanoke, VA 24019		(703) 563-0371

Valtech Corp 99 Hartwell St West Boylston, MA 01583	Welty Trout	(617) 835-6082

LEDs

Fairchild Microwaves Optoelectronics Div 4001 Miranda Ave Palo Alto, CA 94303	Don Staub Bruce Cairns	(415) 493-3100
General Electric Corporate R&D 1 River Road Schenectady, NY 12345	Jack Kingsley	(518) 346-8771
Litronix, Inc 1900 Homestead Rd Cupertino, CA 95014	Tony Heinz	(408) 257-7910
Meret, Inc 1050 Kenter Ave Los Angeles, CA 90049	Dave Medved	(213) 828-7496
Monsanto Electronic Special Products 3400 Hillview Ave Palo Alto, CA 94304	Grant Riddle	(408) 257-2140
Motorola Semiconductors Box 20912 Phoenix, AZ 85036	Francis Christian	(602) 962-3186
RCA Indl Tube Div Dept G New Holland Ave Lancaster, PA 17604	Jim O'Brien	(717) 397-7661
Spectronics, Inc 541 Sterling Dr Richardson, TX 75080	J. R. Biard	(214) 234-4271
Texas Instruments Mail Station 12 PO Box 5012 Dallas, TX 75222	Gene Dierschke	(214) 238-4561

PHOTODIODES

EG&G, Inc 35 Congress St Salem, MA 01970	Ed Danahy	(617) 745-3200
Fairchild Microwave & Optoelectronics Div 4001 Miranda Ave Palo Alto, CA 94303	Bruce Cairns	(415) 493-3100
Hewlett Packard 620 Page Mill Road Palo Alto, CA 94303	Hans Sorenson Stan Gage	(415) 493-1212
Inotech 181 Main St Norwalk, CT 06851	Ray Pennoyer	(203) 846-2041
Monsanto Electronics Special Products 3400 Hillview Ave Palo Alto, CA 94304	Wayne Stewart	(415) 493-3300
Motorola Semiconductors Box 20912 Phoenix, AZ 85036	Dave Durfee	(602) 244-4556
Quantrad Corp 2261 G S Carmelina Ave Los Angeles, CA 90064	Frank Ziemba	(213) 478-0557
RCA Indl Tube Div Dept G New Holland Ave Lancaster, PA 17604	Jim O'Brien	(717) 397-7661
Spectronics, Inc 541 Sterling Drive Richardson, TX 75080	J. R. Biard	(214) 234-4271
Texas Instruments PO Box 5012 Dallas, TX 75222	Ed Harp	(214) 238-3274

UDT, Inc 2644 30th St Santa Monica, CA 90905	Don Dooley	(213) 396-3175

CONNECTORS

Amphenol Connector 2801 South 25th Ave Broadview, IL 60153	Don Warenburg	(312) 345-9000
Deutsch Co Elect Components Div Municipal Airport Banning, CA 92220	Ted Alsworth	(714) 849-6701
ITT Cannon 666 E Dyer Road Santa Ana, CA 92702	Ron McCartney	(714) 557-4700

APPENDIX F

Assumptions for an Economic Analysis of the ALOFT Project

The following assumptions shall be utilized by NELC, NPS students, and NELC contractors in the performance of an economic analysis of the A-7 ALOFT Project:

The external electro-optic adapter units which were required for the ALOFT project would not be the design approach for the multiplexed fiber optic interface in a point-to-point data transfer system or data bus of the future, since the MUX/DEMUX and electro-optic drivers and receivers would physically replace the I/O design presently being utilized in the electrical interface of the peripheral avionic units.

Assuming that next-generation point-to-point data transfer systems are going to make increasing use of electronic multiplexing to reduce the interface density, the resulting increased data rate requires close consideration of the tradeoffs in selecting the interface medium due to increased susceptibility to electromagnetic compatibility (EMC) problems encountered at high data rates.

Three generally recognized methodologies exist at the present time as alternatives for the multiplexed system interface medium which are sufficiently proved to be considered: coaxial cables, twisted pair, and fiber optics. Millimeter waveguide technology has not sufficiently developed at this time to be a viable alternative.

Once the assumption of multiplexing is made, the transmission of the data over any one interface channel requires four basic components as the building blocks for any point-to-point interface system: a driver, a cable, a connector, and a receiver. In a data bus system only one additional component is required above the basic building blocks: an access coupler.

Due to the various types of connections required to install a data transfer system in a particular vehicle or platform, there exists a subset of the connector building block consisting of the different varieties of connectors. These varieties can be generally classified as: single-channel bulkhead, single-channel pressure bulkhead, multichannel bulkhead (or rack/panel), and multichannel pressure bulkhead. A splice connector is not an autonomous part of this

subset because the basic design of a single-channel bulkhead connector can be adapted to fulfill the requirement for a splice at no major change in cost. A printed circuit card connector is a possible variety, but is also an adaptation of the single-channel bulkhead connector.

The optical signal driver can be considered to be dimensionally the same size as its electrical counterpart since both can be created from discrete amplifier circuitry or hybrid or integrated circuits. The same can be basically stated for the signal receiver. The only difference that may occur in the evolving design of optical drivers and receivers from their electrical counterparts is a modular optical component such as the light source or light detector that can be inserted into or removed from the discrete or hybrid circuitry. The necessity of this modularity depends on the reliability that is achieved by the manufacturers of the optical components. If the optical components become as reliable as the rest of the driver or receiver circuitry, modularity will not be required. This contingency also has major bearing on the maintainability that will evolve for optical drivers and receivers.

For installation and handling considerations, the fiber optic cable can be considered to be susceptible to the same requirements as the coaxial cable.

Preliminary review of the performance capability of twisted-pair components leads to the preliminary conclusion that twisted pair is not a valid alternative for a multiplexed interface due to inability to handle high data rates without extreme susceptibility to EMC problems. This preliminary analysis requires further analysis to validate the conclusion. However, for initial analysis purposes no effort will be made to gather the component data for the twisted-pair case until this conclusion is refuted by further analysis.

The performance, cost, weight, and power consumption data for the components required for a coaxial interface are readily available from commercial manufacturers. A review of the data has led to the selection of candidate coaxial components that could have been used in a coaxial version of the ALOFT interface. The identity and data for these components are included in table 1C. These components shall be utilized as the coaxial interface baseline in the analysis.

The performance, cost, weight, and power consumption data for the fiber optic components required are not readily available from commercial manufacturers. NELC Code 2540 (Fiber Optics Systems Branch, Electro-optics Technology Division) has compiled performance requirements for each of the basic fiber optic components that are projected to be required in FY77 to fulfill a fiber optic point-to-point interface system requirement in an aircraft data transfer system. These performance requirements are constrained by a MIL-E-5400P Class 2 environment. These performance requirements for each building block are attached as appendix A to this concept report. The economic analysis will gather the cost, weight, power consumption, and any other required data for the fiber optic components. This data gathering will be an iterative approach based on the Delphi predictive analysis method.

Source: NELC TD-435

BIBLIOGRAPHY

1. Air Force Avionics Laboratory Technical Report AFAL-TR-73-267, Part 1, Fiber Optics and Related Technology, by D.D. Matulka and others, p. 1-147, November 1973.

2. Army Electronics Command Research and Development Technical Report EMCOM-4271, Application of Fiber Optic Technology to Army Aircraft Systems, by CW3 Richard D. Parent, p. 1-53, November 1974.

3. Army Strategic Communications Command Report AD-754 566, Optical Fiber Links for Telecommunications, Part 1, by Stephan F. Fulghum, Jr., 1LT, with James J. Burke, Dr., p. 36, December 1972.

4. Anderson, Rodney, Galileo E/O Corp., Telephone conversation with author, 15 August 1975.

5. Ayres, R. U., Technological Forecasting and Long-Range Planning, p. 8, McGraw-Hill, 1969.

6. "Bell Crashes the 2 dB/km Barrier," Electro-Optical Systems Design, p. 4, August 1974.

7. Biard, J.R., Spectronics, Inc., Telephone conversation with author, 15 August 1975.

8. Bielawski, W.B., "Low-Loss Optical Waveguides: Current Status," Electro-Optical Systems Design, p. 22-28, April 1973.

9. The Boston Consulting Group, Perspective on Experience, The Boston Consulting Group, Inc., 1970.

10. Cetron, Marvin J., Technological Forecasting, p. 149, Technology Forecasting Institute, 1969.

11. Chief of Naval Operations letter dated 3 July 1974.

12. Currie, Malcolm R., Dr., memo dated 6 August 1973.

13. Electronic Design News, p. 12-13, 15 February 1972.

14. Ellis, John, LCDR USN, NELC (Code 1640), numerous telephone calls throughout 1974-75.

15. Encyclopedia Britanica, V. 10, p. 475, 1967.

16. Encyclopedia of Science and Technology, V. 9, p. 536, McGraw-Hill, 1964.

17. Fisher, G.H., Cost Considerations in Systems Analysis, p. 10, American Elsevier, 1971.

18. Free, John, "The Coming Age of Fiber Optics: How wires of glass will revolutionize communications," Popular Science, p. 82-85, August 1975.

19. Freiberger, R., Corning Glass Works, Telephone conversation with author, 18 August 1975.

20. Gordon, T.J., and Helmer, Olaf, Report on a Long-Range Forecasting Study, Report P-2982, The Rand Corporation, Santa Monica, September 1964.

21. Hirschman, W.B., "Profit from the Learning Curve," Harvard Business Review, p. 125, January-February 1964.

22. Ikegama, T., and Suematsu, T., "Carrier Lifetime Measurement of a Junction Laser Using Direct Modulation," IEEE Journal of Quantum Electronics, v. QE-4, p. 148, April 1968.

23. Jantsch, Erich, Technological Forecasting in Perspective, p. 137, Organization for Economic Co-Operation and Development, Paris, 1967.

24. Kahn, Herman, and Bruce-Briggs, B., Things to Come, p. 186-188, MacMillan, 1972.

25. Kapany, N.S., Fiber Optics, Principles and Applications, p. 1-10, Academic Press, 1967.

26. "The Light Wave of the Future," Business Week, p. 49, 1 September 1975.

27. Lisita, M.P., Bereyhinskii, L.I., and Valakh, M. Ya., Fiber Optics, Israel Program for Scientific Translations, p. 56, 1972.

28. Naval Electronics Laboratory Center Report 405-103, Fiber Optics Communication.

29. Naval Electronics Laboratory Center Technical Note 3000, Economic Analysis and Life Cycle Cost Model for Naval Telecommunications Systems, by R.A. Greenwell and others, p. 18, 30 June 1975.

30. Naval Electronics Laboratory Center Technical Report 1891, Fiber- and Integrated-Optic Communications Technology, by W.E. Martin and D.J. Albares, 24 August 1973.

31. Naval Electronics Laboratory Center Technical Document 435, A-7 ALOFT Economic Analysis Development Concept, by J.R. Ellis and R.A. Greenwell, p. 15, 7 July 1975.

32. Naval Research Laboratory Memorandum Report 3004, EOTPO Major Issue Review, Fiber Optics and Integrated Optics, EOTPO Report No. 20, p. 2, April 1975.

33. Naval Electronics Laboratory Center Technical Report 1763, Revision 1, Transfer of Information on Naval Vessels Via Fiber Optics Transmission Lines, by H.F. Taylor, p. 5, 3 May 1971.

34. Novotny, G.V., "Fiber Optics for Electronics Engineers," Electronics, p. 35, No. 22, 1962.

35. Ohlhaber, R.L., "Long Path Transmission in Fiber Optics," Electro-Optical Systems Design, p. 18-21, August 1971.

36. "Peek-A-Boo, I See You," Electro-Optical Systems Design, p. 5, June 1973.

37. Rand Corporation, Military Equipment Cost Analysis, p. 94, 1971.

38. Taylor, H.F., Caton, W.M., and Lewis, A.L., "Data Bussing with Fiber Optics," Naval Research Review, p. 12-25, February 1975.

INITIAL DISTRIBUTION LIST

		No. Copies
1.	Defense Documentation Center Cameron Station Alexandria, Virginia 22314	2
2.	Library, Code 0212 Naval Postgraduate School Monterey, California 93940	2
3.	Department Chairman, Code 55 Department of Operations Research and Administrative Sciences Naval Postgraduate School Monterey, California 93940	1
4.	LCDR J. M. McGrath 511 South Newland St. Denver, Colorado 80226	1
5.	LCDR K. R. Michna 1324 Jackson Street North Chicago, Illinois 60064	1
6.	Dean of Research Administration Code 023 Naval Postgraduate School Monterey, California 93940	1
7.	Professor C. R. Jones, Code 55JS Naval Postgraduate School Monterey, California 93940	5
8.	Associate Professor B. R. Pierce, Code 6423 Naval Postgraduate School Monterey, California 93940	1
9.	CDR D. Forsgren CNO (OP-982E2) Washington, D. C. 20350	1
10.	Chief of Naval Material NMAT-03422 Washington, D. C. 20360	1

11. A. D. Klein 2
Naval Air Systems Command
AIR-360G
Washington, D. C. 20361

12. CAPT R. N. Winkel 1
Naval Air Systems Command
AIR-533
Washington, D. C. 20361

13. Andrew S. Glista 2
Naval Air Systems Command
AIR-52022
Washington, D. C. 20361

14. N. Butler 1
Naval Electronic Systems Command
ELEX-304
Washington, D. C. 20360

15. K. C. Trumble 1
Air Force Avionics Laboratory
AAM
Wright-Patterson AFB, Ohio 45433

16. J. Ramage/Gene James 1
AFFDL/FGA
Wright-Patterson AFB, Ohio 45433

17. CWO R. Parent, USA 1
U. S. Army ECOM
Avionics Lab, AMSEL-VL-A
Ft Monmouth, New Jersey 07703

18. T. R. Coleman 1
LTV Vought Systems Division
Code 2-14000
P. O. Box 5907
Dallas, Texas 75222

19. R. Betts 1
IBM Federal Systems Division
Owega, New York 13827

20. Commander
Naval Electronics Laboratory Center
271 Catalina Blvd
San Diego, California 92152
Attn:

Code 1640 (J. Ellis)	2
Code 235 (R. Greenwell)	5
Code 220 (D. Williams)	1
Code 2500 (T. Meador)	1
Code 4400 (G. Holma)	1
Code 6700	1

Thesis 163996
M188475 McGrath
c.1 An approach to the estimation of life cycle costs of a fiber-optic application in military aircraft.